The Providence Island Formation in the Northern Appalachian Region - a Lower-lower Middle Ordovician analogue to recent arid-semiarid tidal-flat carbonates of the Persian Gulf Trucial Coast

A thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree of
Master of Science
Department of Geological Sciences

Mauricio Roma Hernandez
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ABSTRACT

The Providence Island Formation of Early-early Middle Ordovician age occurs in the Champlain Valley and adjacent areas in eastern New York, western Vermont, and southern Quebec. The unit forms part of a carbonate shelf sequence which occupied the eastern margin of the North American continent from Newfoundland to Alabama, and its lithology is representative of the dolostone lithofacies that characterizes the uppermost Beekmantown Group in this region.

This is the first study documenting depositional environments, diagenesis, and stratigraphic correlations of the Providence Island Formation. This formation consists, in decreasing abundance, of dolostones, limestones, shales, and dedolostones. The dominantly fine grain size of the rocks as well as the presence of sedimentary and diagenetic features such as homogeneous and mottled structures (biogenic), stromatolites, mudcracks, herringbone cross-bedding, fenestral cavities, evaporites or their pseudomorphs, diapiric structures, and solution-collapse breccias indicate that these sediments record tidal flat paleoenvironments. These are low tidal flat, high tidal flat and, to a lesser extent, subtidal and supratidal settings similar to those existing in modern arid, restricted marine tidal flats of the Persian Gulf Trucial Coast. The lithofacies and their inferred setting include:

(1) Homogeneous dolostone: subtidal to lower intertidal or, occasionally, supratidal (sabkha).

(2) Homogeneous limestone: lower intertidal.

(3),(4) Mottled dolostone/limestone: lower intertidal.

(5),(6) Laminated dolostone/limestone: upper intertidal.

(7) Skeletal limestone: mostly upper intertidal.

(8) Dedolostone: mostly upper intertidal to supratidal.

(9) Shale: subtidal-lower intertidal to supratidal.

Most laminated dolostones and limestones represent stromatolites. On the basis of composition and texture, the alternating laminae are grouped into two types:

- Dolomitic facies: (I) FM-CPA: (F-fine, M-matrix - C-coarse, P-pyritic, A-allochemical-terrigenous) and (II) F-CA.

- Calcareous facies: (I) Mc-SPA: (Mc-micrite - S-sparite, P-pyrite, A-allochemical-terrigenous) and (II) Mc-SA.

Some laminae are transitional types between these end members. Storms appear to have been the most important factor controlling the type of alternating laminae.

The dolostone portion of the formation displays features that are characteristic of selective, sabkha diagenesis. These include the fine-grained size of the dolomite crystals, the preservation of primary structures (burrows, mudcracks, etc.), and the presence of gypsum and anhydrite crystals as well as their nodular pseudomorphs.

Textural evidence suggests a diagenetic sequence of (1) synsedimentary cementation (or cohesiveness (?)), (2) precipitation of evaporites, dolomitization, and pyritization, (3) precipitation of calcite, (4) dissolution of evaporites and void infill by chert or carbonates, (5) dedolomitization, and (6) compaction and stylolitization. The most important mechanism for the precipitation of evaporites and subsequent dolomitization appears to have been "flooding - reflux" in a highly evaporative environment. Here, downward percolating brines with a high Mg/Ca ratio induced the dolomitization of the sediment in contact with this fluid. The conditions favoring the alternation of dolostones and limestones are unknown.

The upper part of the formation may be divided into four members: the lowest one is about 2 - 3 m thick and is made up of limestones and is followed by a dolostone - dominated sequence (15 m, or more, thick). The overlying calcareous member is similar to, but 0.5 - 1 m thicker than, the lower one. It is overlain by a second dolomitic member which could be considered as two units: the lower one (2.5 m) is characterized by laminated facies whereas the upper one (4.5 m or more) consists mainly of homogeneous and mottled facies.

The formation seems to be more than 100 m thick in the central portion of the outcrop belt and reaches approximately 160 m in the area of Shoreham, Vermont. Extensive erosion after the time of deposition of the

formation appears to be the cause of lateral differences in thickness, particularly to the south where the formation pinches out and disappears. The post-Beekmantown unconformity probably reflects such an erosive event.

The tidal flats are thought to have developed on a tectonically stable area. Also, it seems that the flats were adjacent to both a very shallow lagoon which possibly was separated from the open (Iapetus) ocean by a physical barrier to the east and the shoreline to the west.

ACKNOWLEDGEMENTS

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Finally, my deepest thanks to my parents and sister for their constant support and love.

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1.- INTRODUCTION

1.1 Geologic setting

Geologically, the area of study (Fig. 1.1) has been the location of deposition of Cambrian fluvial to marine clastics (lower Postdam and Ticonderoga Formations), Cambrian-Ordovician (Beeekmantown Group) and Middle Ordovician (Chazy, Black River, and Trenton Groups) shelf carbonates, which deepen upward into marine argillites and black shales (Trenton Group). The specific depositional environments of these deposits are shown in Figure 1.2.

These deposits have been variably affected by compressional deformation in the continental foreland by an arc collision during the Taconic Orogeny (Chapple, 1973; Rowley and Kidd, 1981). As a consequence, they have been overriden by the Taconic Allochthon. The parautochthonous shelf deposits are thrusted over themselves near the complex allochthonous front (Fig. 7.2A,B).

The Beekmantown Group comprises a thick sequence of mixed carbonate-siliciclastic deposits ranging in age from Late Cambrian (Upper Postdam, Ticonderoga, and Whitehall Formations) to Early and early Middle Ordovician (Great Meadows, Spellman, Fort Cassin, and Providence Island Formations). The Providence Island Formation (Late Canadian and middle Whiterockian) (Landing and others, submitted)

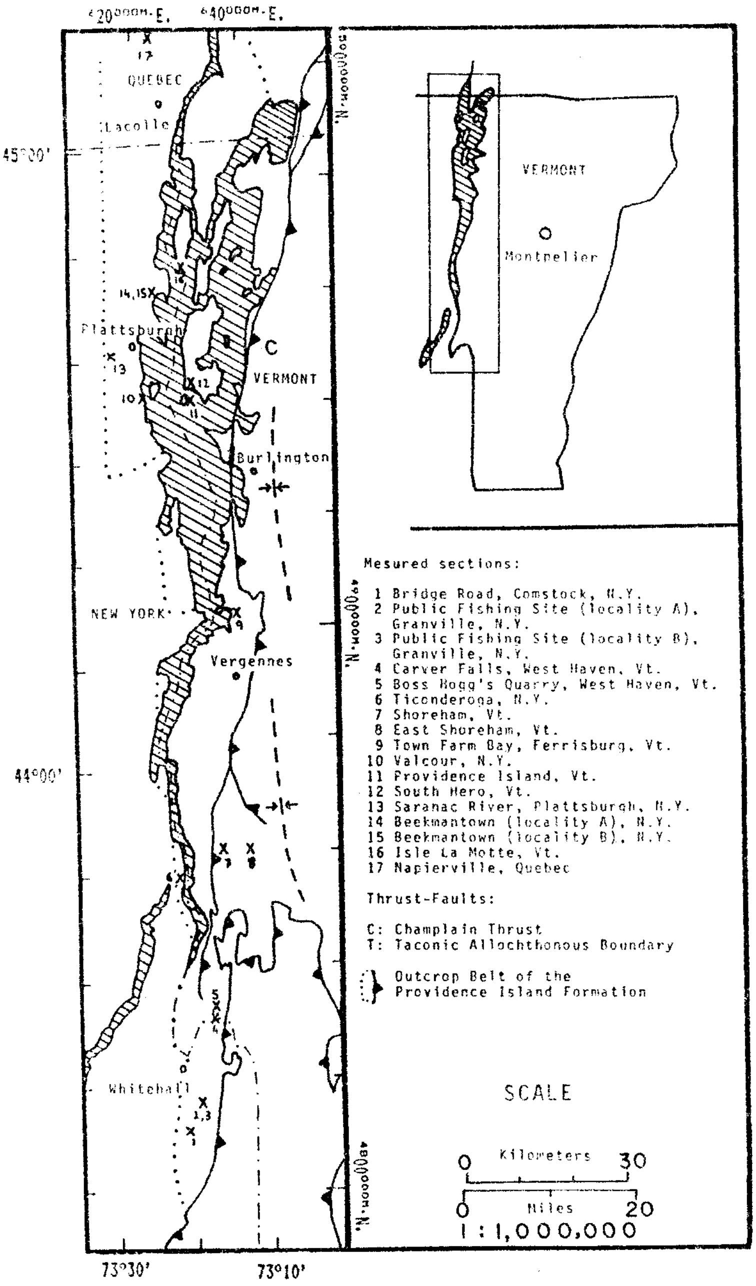

Fig. 1.1.- Index map showing outcrop belt of the Providence Island Formation, location of the measured sections, and major structural features of the region (modified from Welby, 1961).

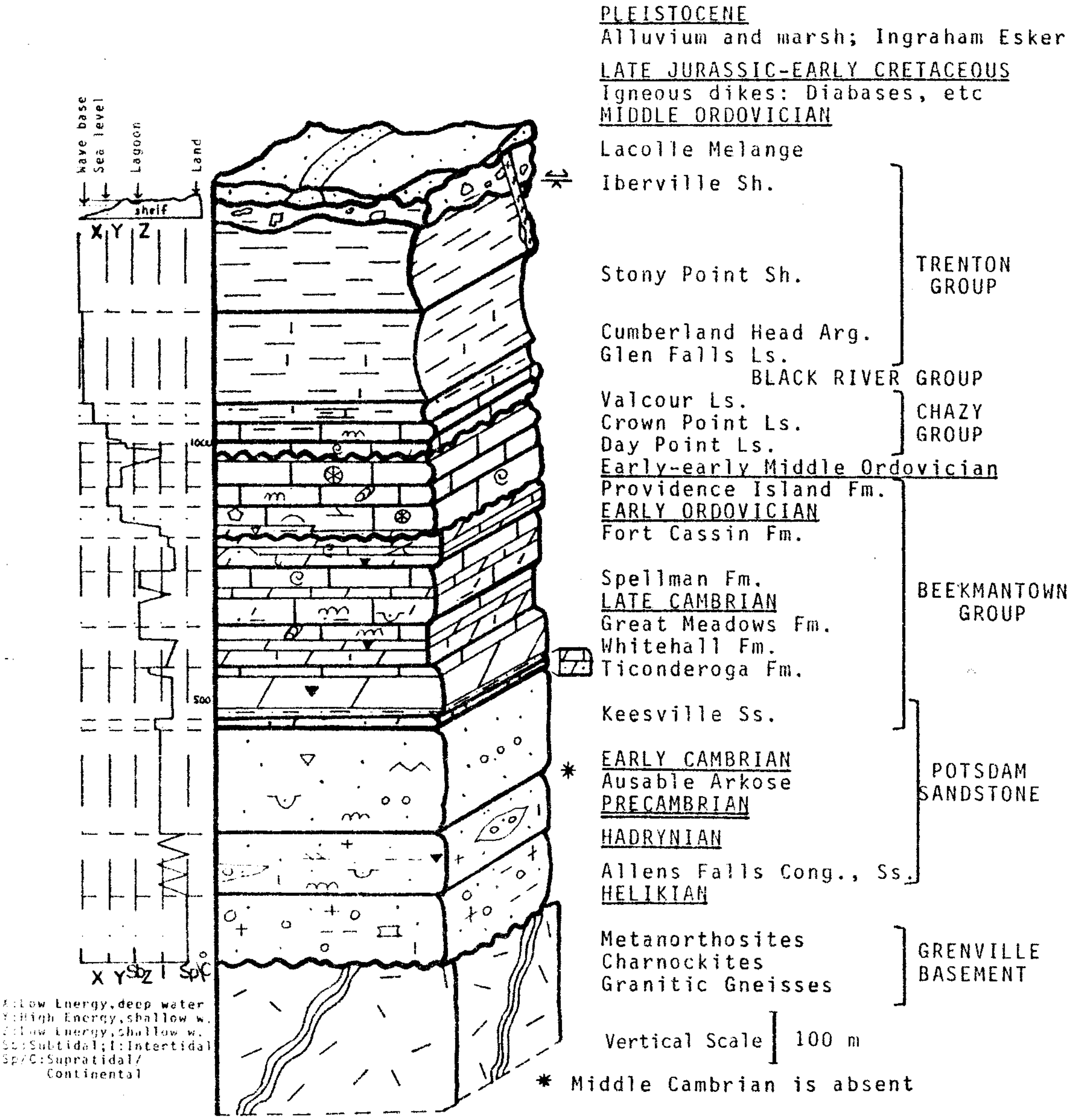

Fig. 1.2.- Generalized stratigraphy and depositional environments of the rocks of the central-northern Champlain Valley, New York-Vermont. Legend is in Figure 9.16.

constitutes the upper part of the Beekmantown Group (Fig. 1.2). This formation crops out in a narrow north-south belt located between the Precambrian Adirondack Mountains (New York) and the Champlain Thrust-Taconic Allochthonous Front (New York-Vermont), without major lithological changes. The outcrop belt is about 210 km long (from Napierville, Quebec, to Fort Ann, New York) and 17 km wide along the Lake Champlain Valley (Fig. 1.1).

The Providence Island Formation is composed primarily of dark fine-grained dolostones with intercalations of fine- to coarse-grained limestones and medium-grained dolostones. It conformably overlies the Fort Cassin Formation. The top of the Providence Island Formation is marked by an unconformity, the Post-Beekmantown Unconformity, which separates Early and early Middle Ordovician from younger Middle Ordovician rocks.

1.2 Objective

Not much has been published on the detailed characteristics of the different lithofacies of the formation or on their vertical succesion and spatial distribution. Therefore, their interrelationships, depositional environments, diagenetic modifications, vertical and lateral changes, as well as theirpaleogeographic and tectonic implications are far from resolved. Thus, the object of this study is to fill in these gaps by careful analysis of the lithofaciess of the

Providence Island Formation and comparison with Holocene analogues. The reconstruction of the depositional environments is possible by the preservation of primary sedimentary structures and textures.

1.3 Previous work

Early workers described the characteristics of the Providence Island Formation while mapping or describing the general geology of specific areas. Brainerd and Seely (1890) referred to the Providence Island Formation as "Division E" of the "Calciferous". This division was characterized by fine-grained, magnesian limestone beds, occasional fossiliferous layers, and rarely occurring thin layers of slate in exposures to the east of the town of Shoreham, Vermont. Clarke and Schuchert (1899) replaced the older term "Calciferous" with the present term " Beekmantown". Ulrich (in Ulrich and Cooper, 1938) first applied the term "Providence Island Dolomite" to equivalent beds of "Division E" exposed on Providence Island, Vermont, in the northern part of Lake Champlain. Cady (1945) suggested the name "Bridport Dolomite" for other correlative rocks exposed on the hills in the southeastern part of the town of Bridport. Other early workers that have described the Providence Island Formation during regional geological study include, among others, Erwin (1957), Welby (1961), and Fisher (1968, 1985).

It seems more appropiate to use the term "Providence Island" because the formation is more continuous and better exposed in Providence Island than in Bridport. In addition, the name "Providence Island Formation" seems more accurate than "Providence Island Dolostone" because the formation contains at least two significant limestone units as well as minor intercalations of shale.

1.4 Procedure

The interpretation presented here is based on investigation of 33 sections representing a composite 455 m of section. Eighteen of these sections are in the Providence Island Formation (316 m) and the rest (139 m) represent underlying and overlying deposits. The sections have been extensively sampled to evaluate the vertical succesion and distribution of the sedimentary, diagenetic, and environmental characteristics of the different lithofacies (Figs. 9.17 to 9.33). For this purpose, a total of between 2,000 and 2,500 samples have been slabbed and etched in order to study the composition, fabric, and structures. Also, 46 selected thin sections stained with combined Alizarine Red S and potassium ferricyanide solutions have been examined. All the stratigraphic sections have been compared in order to recognize possible correlations.

2.- LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

2.1 General Statement

The lithofacies have been defined mainly by their composition, texture, and sedimentary structures. Although many of the rocks of the formation appear homogeneous, they frequently show levels of different sub-lithofacies when studied in detail.

The Providence Island Formation consists mainly of nine lithofacies that represent tidal flat deposits. Eight of these are carbonates and the other is a shale. The carbonate lithofacies are represented by homogeneous dolostones, mottled dolostones, laminated dolostones, homogeneous limestones, mottled limestones, laminated limestones, skeletal limestones, and dedolostones. In order to avoid confusion, the term "dolomite" refers to a mineral constituent whereas "dolostone" is a rock type. The classification given for carbonates is useful in helping to determine environmental implications. The identification of their depositional environments is based on the recognition of features similar to those found on modern carbonate environments. Of the two major carbonate types, dolostones are discussed before limestones, and within each of these two categories the order of discussion reflects increasing subaerial exposure within the tidal flat.

2.2 Homogeneous dolostone

This lithofacies is similar to the mottled dolostone (2.3) in characteristics and interpretation. Homogeneous dolostones are commonly thicker than and are transitional into mottled dolostones. Observations should be made with care since some apparently homogeneous rocks could be mottled because the mottling is indistinct. In this study, the designation "homogeneous" dolostone is applied when mottling occupies less than 0.1% of the rock volume.

2.3 Mottled dolostone

Description

The rocks of this lithofacies are fine-grained and are mainly characterized by the presence of mottled structures (Fig. 2.1) (discussed below). The bedding varies from a few centimetres to a maximun of 2 m in thickness and averages 25 cm to 75 cm. Mottled beds occasionally are seen to form stratigraphic intervals up to 4 m thick. Beds having a slaty appearance are relatively common. The rock color varies on a fresh surface from a medium gray (N5) to a dark gray (N3) with the most common color being medium dark gray (N4). On weathered surfaces, the color varies from pale yellowish orange (10 YR 8/6) to pinkish gray (5 YR 8/1) or yellowish gray (5 Y 8/1). The most common weathering color is a very pale orange (10 YR 8/2) or a grayish to a dark yellowish orange (10 YR 7/4 to 10 YR 6/6). The latter color only occurs if the rock is in frequent contact with fresh water (lake or river). The rock emits a fetid odor when freshly broken. This odor is probably H_2S.

In decreasing order of abundance, the most significant sedimentary structures in this lithofacies are mottling, mudcracks, scours, intraclasts, and fenestral cavities. However, mudcracks have not been observed in thick bedded homogeneous dolostones. Diagenetic structures commonly are chert or carbonate nodules, solution-collapse breccias, stylolites, and some white quartz or carbonate veins (Fig. 2.2). Mottling consists of small irregularly shaped areas (mottles), usually less than 1 cm in average diameter, that have different colors on fresh and weathered surface (Fig. 2.1). The smaller mottles generally have a more spherical cross section. Mottles can be both lighter or darker than the surrounding material. On fresh surfaces lighter mottles are more frequent and show a more pronounced yellowish orange color on the weathered surface. Petrographically, the difference between lighter and darker mottles is due to variations in the texture and in the relative proportions of their components. The petrographic characteristics of the mottled structures are discussed after examining the general compositional and textural features of these rocks. For details on the other structures see chapters 3 and 4.

The predominant texture is hypidiomorphic granular. The major component is dolomite. Accesory components are

Fig. 2.1.- Polished and etched slab of dolostone showing burrows (e.g. just above the center) and mottled structures (e.g. just below the center). Note that mottling appears to represent burrow-infills. Isle La Motte Section (23.5 m). Arrow indicates top.

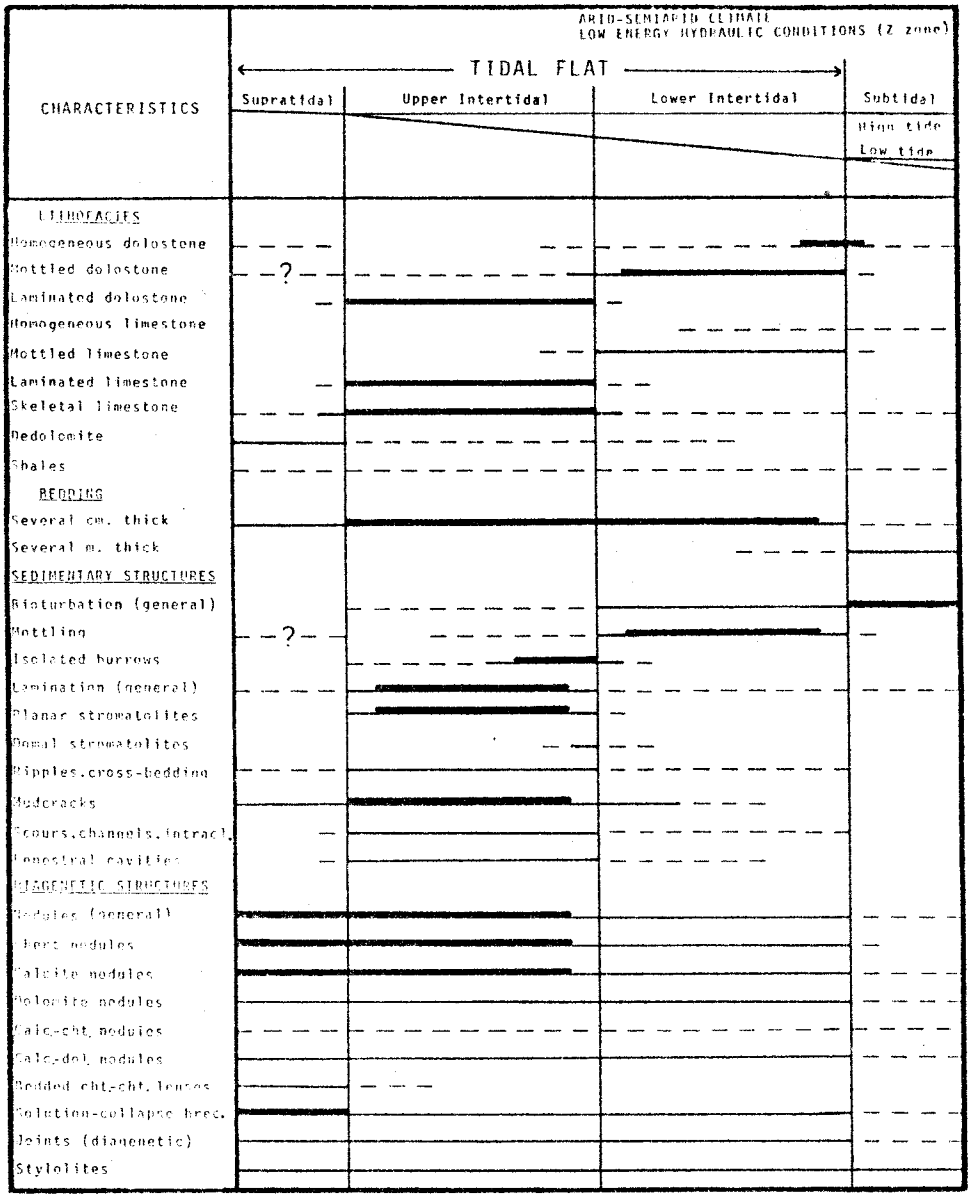

Fig. 2.2.- Inferred characteristics of the depositional environments of the Providence Island Formation. Their distribution and relative abundance.

detrital quartz grains, pyrite, carbonaceous material, clays (?), and, more rarely, calcite, K-feldspar, muscovite, zircon, tourmaline, fossil fragments, pellets, chert, authigenic quartz, gypsum, anhydrite, and Fe-oxides.

Dolomite constitutes approximately 90% of the rock and has a grain size ranging between 10 um and 100 um or more but is generally 25 um to 35 um. The average grain size generally increases with the detrital content. Dolomite commonly occurs as a mosaic of subhedral cloudy or clear crystals and, more rarely, as euhedral or anhedral crystals (Fig. 2.11). Euhedral dolomite rhombs occur where crystals are isolated from each other by dark intercrystalline matrix material. Subhedral crystals show irregular crystal faces that result from the intersection of two or more crystal boundaries. Anhedral crystals only occur in occasional areas where crystals are closely clustered together. The rhombs are often poikilitic with inclusions of matrix material and, to a lesser extent, of pyrite. These inclusions sometimes parallel the crystal faces (Fig. 2.11). The coarser dolomite rhombs generally show compositional zoning with euhedral, slightly ferroan cores surrounded by clear syntaxial overgrowths (Fig. 2.12). The cores are brownish, pseudopleochroic, and cloudy due to very finely disseminated inclusions of apparent matrix material (discussed below). Very rarely, two or more zones of cloudy dolomite are observed in the larger crystals (Fig. 2.11).

Occasionally the dolomite crystal's outer rim is molded partially around or completely includes smaller minerals such as detrital quartz or, more rarely, pyrite. In a few instances, the dolomite crystals penetrate and reabsorb the pre-existing quartz grains. The former case occurs when an initially planar dolomite crystal face is in contact with the detrital grain, and the latter when an angle of the crystal is in contact with the detrital grain. Ferroan dolomite occasionally occurs, especially in detrital quartz-rich areas, as intergranular, anhedral crystals between the dolomite rhombs and the quartz grains. This phase probably represents a cement.

Euhedral to anhedral pyrite crystals commonly occur as intergranular phases or as fine-grained inclusions within the dolomite rhombs (especially in the overgrowths) in concentrations usually not exceeding 1% or 2% (Fig. 2.11 and 2.12). Their grain size commonly varies from 5 um to 60 um with an average size being 20 um to 25 um. The grain size of the pyrite inclusions in dolomite usually increases from the cores to the edges of the dolomite crystals. Coarser pyrite grains or crystals commonly are associated with coarser detrital quartz or dolomite crystals. Pyrite is occasionally seen in the form of sub-spherical framboids.

Detrital quartz commonly occurs as relatively well sorted, angular to sub-angular, clear, grains that are scattered throughout the rock. Its concentration varies between 1% and 35% but rarely exceeds 3%. Locally, it may appear concentrated in thin laminae or small lenses. Quartz grains and dolomite rhombs (especially the cloudy crystals or central cores) are of comparable size. Coarser grains often show undulous extinction and are associated with larger dolomite crystals.

Microcline, plagioclase, muscovite, tourmaline, and zircon are always associated with detrital quartz. All are very well sorted with a grain size averaging 35 um. Their relative proportions are shown in Figure 2.3. Microcline occurs mainly as subhedral or, more rarely, euhedral crystals. The latter possibly consists of sub-angular detrital grains surrounded by a syntaxial overgrowth of authigenic feldspar (Buyce and Friedman, 1975). Because the detrital microcline is not altered, such authigenic overgrowths cannot be observed under the microscope. Plagioclase occurs as sub-angular grains. Muscovite laths sometimes are partially included in the dolomite crystals. Tourmaline and zircon appear as more-or-less rounded grains. The latter only appears in trace amounts.

Fossil fragments are also disseminated throughout the rock. They are more abundant in quartz-rich beds or horizons, although generally in concentrations not exceeding 0.5%. Most of the skeletal fragments are phosphatic and are thought to be pieces of linguloid brachiopods based on their resemblance to Linguella fragments found within the basal

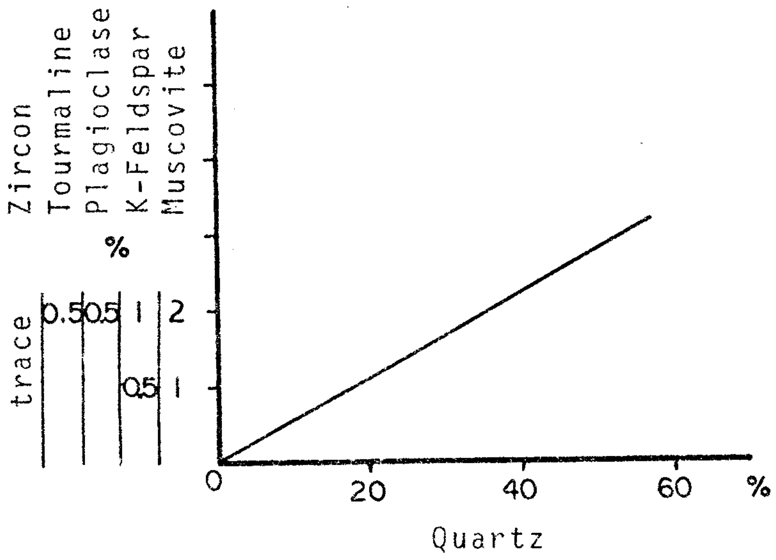

Fig. 2.3.- Approximate relative proportions of the terrigenous constituents with respect to detrital quartz in the carbonate lithofacies of the Providence Island Formation.

clastics of the Chazy Group. They are small, slightly curved and generally less than 0.6 mm by 40 um in length and width, respectively. Occasionally, some prismatic fossil fragments are dolomitized but they appear to preserve their original internal structure by the presence of non-crystalline amorphous inclusions. E. Landing (personal commun., 1985) identified this structure as either an ostracod or a trilobite fragment. Rarely, isolated rectangular crystals of dolomite, up to 0.6 mm in size, are present. Such crystals show uniform extinction and may represent dolomitized pelmatozoan fragments. Skeletal fragments are only abundant in local thin grainstone intercalations where they are associated with intraclasts (2.8). They correspond to trilobites, pelmatozoans, brachiopods, ostracods, gastropods, and nautiloids (Fig. 2.15).

Pellets and, to a lesser extent, other peloids occasionally occur as dark, sub-spherical particles that are either disseminated or concentrated at certain horizons of the rock. Their size may reach 1 mm or more but commonly averages between 25 um and 150 um. Pellets and matrix material generally have the same mineral composition although the carbonaceous and pyrite content is usually slightly higher in pellets. Pellets may be obscured when the relative proportions of the components of the matrix and pellets are nearly identical.

The intergranular matrix consists mainly of a dark brown, micron-size aggregate of dolomite, pyrite, carbonaceous material, clays (?), and Fe-oxides. The amount of matrix in the rock varies between 1% and 35% with common values near 10%. The identification of clays is rather difficult because of their intimate association with the other dark phases. Matrix constituents also may be included within later diagenetic crystals such as the cloudy cores of dolomite, authigenic quartz, or gypsum crystals (Fig. 2.11). More rarely, the intergranular material consists of clear ferroan dolomite or calcite-spar that range in size from 30 um to 90 um. These coarser phases are generally associated with more detrital and coarser grained horizons.

As discussed above, mottles can be lighter or darker than the surrounding rock. The lighter areas are slightly coarser grained and commonly are richer in terrigenous material, fossil fragments, intergranular ferroan dolomite and calcite, and, to a lesser extent, relatively large pyrite crystals. However, they have a lower content of dark brown matrix than the darker areas. The typical content of matrix in lighter areas is 8% and 12% in darker areas. The matrix of lighter mottles contains 1% and 6% of carbonaceous material and pyrite, respectively, in contrast to 8% and 2%, in darker ones. In both lighter and darker mottles, the matrix has similar amounts of clays (5% or less) and carbonates (1%). Darker mottles may contain up to 1% Fe-oxides.

This lithofacies occasionally displays nearly black irregular areas that are up to 3 cm in average diameter. These areas usually consist of 40% subhedral to euhedral dolomite, 1% detrital quartz, and traces of muscovite, K-feldspar, and authigenic quartz. The rest is a dark brown to black matrix composed of an aggregate of micron-sized pyrite (30%), Fe-oxides (25%), and carbonaceous material (5%) with minor amounts of clays (?) and carbonates. Elongated black pockets occur within these dark areas. These pockets are sub-parallel to bedding and are roughly 0.6 mm by 0.2 mm in size. They contain micron-sized pyrite (60%) and carbonaceous material (40%) and occasionally enclose a few subhedral to euhedral dolomite rhombs. The pockets are generally rimmed by a 5 um to 15 um wide film consisting of micron-sized pyrite (90%) and carbonaceous material (10%).

Interpretation

Several lines of evidence suggest that the dolostones of this lithofacies represent carbonate muds that have been deposited in the lower intertidal portion of a tidal flat which developed under arid and restricted marine conditions (Fig. 2.2). Features diagnostic of tidal mud flats are the muddy nature of the original sediment, the presence of both mudcracks (chapter 3.2) and fenestral cavities (3.5), and the association of this lithofacies with interbedded tidal flat stromatolites (2.4). The muddy nature of the sediment is inferred by a) the presence of mudcracks, b) the inferred cohesiveness of the original sediment (3.1), and c) the attribution of small dolomite rhombs to preferential growth of these phases in lime mud as inferred from Mississipian carbonates (Murray and Lucia, 1967).

The presence of early diagenetic features, such as evaporite crystals, evaporite pseudomorphs composed of carbonate and chert (4.1), and solution-collapse breccias (4.3) suggests an arid evaporative environment (Aitken, 1981). Restricted marine or low energy hydraulic conditions are inferred from the type of lithology, originally a lime mud, and by the apparent low diversity of the biota in this as well as the other lithofacies (2.8) (Wilson, 1975).

Mottling probably results from the burrowing and browsing activities of organisms. This interpretation is based on observations of mottled horizons within laminated lithofacies where the mottling is clearly related to the filling of the burrows (Fig. 2.1). Mottled structures are thought to be characteristic of the lower intertidal zone because analogous features commonly characterize this part of modern tidal flats (James, 1984).

It is believed that bioturbation is mainly restricted to this part of the tidal flat since it is more frequently covered by water and hence, the salinities are probably only slightly above normal. In upper intertidal or supratidal areas the salinities are probably too high to be tolerated by burrowing and browsing organisms (Bathurst, 1975; Friedman and Sanders, 1978).

The small textural and compositional differences between the mottles and the rest of the rock are probably due to physical and chemical changes produced in the sediment by bioturbation (Moore and others, 1952). However, there is the possibility that some mottling could have originated by diagenetic processes (Conway and Friedman, 1984).

Many homogeneous carbonate rocks are known to reflect extensive bioturbation (Friedman and Sanders, 1978). The gradual transition from mottled to homogeneous rocks may represent a shift from a partial to a total reworking, respectively, of the original sediment and hence, a change from slightly elevated to near normal salinities in the depositional environment. As a result of this, homogeneous lithofacies, especially the thicker bedded types (Reeckman and Friedman, 1982), are thought to be closer to the subtidal-intertidal boundary. Thus, homogeneous rocks, several meters thick, probably have been deposited under subtidal conditions (Fig. 2.2). An alternative is that some homogeneous or mottled beds may reflect rapidly deposited sediments which have not or have been weakly bioturbated. However, many of these beds were originally up to 1 m or more in thickness and rapid deposition of thick units is a rarely documented process in modern, restricted marine, muddy tidal flats.

Supratidal deposits (sabkha type) are in many cases difficult to distinguish from thin-bedded homogeneous subtidal deposits because modern supratidal deposits are commonly composed of typical subtidal particles that have been deposited from sediment-charged waters during storms (Shinn, 1983), by aeolian processes (Lindholm, 1969) or, possibly, by a combination of both. For this reason, it is thought that homogeneous beds, several centimeters thick, containing significant amounts of terrigenous material (2.11), solution-collapse breccias (4.3), evaporite crystals or evaporite pseudomorphs (4.1 and 4.2) as well as dedolostone horizons (2.9) probably represent supratidal sabkha deposits. These type of deposits are not abundant in the formation (Fig. 2.2). The presence of a supratidal sabkha within the depositional environment of the Providence Island is also inferred in chapters 3.3, 4.2, and 5.2.

2.4 Laminated dolostone

Description

The rocks are in most cases fine grained and are characterized by their laminated structures (discussed below). Bedding generally varies from a few centimeters to 1.5 m in thickness in this lithofacies with the most common values being between 20 cm and 60 cm. The beds are occasionally irregular in thickness and may show a slaty appearance.

On the fresh, as well as on the weathered surface, the rock color is similar to mottled or homogeneous dolostones. However, when mottled and laminated horizons alternate within the same bed, the latter frequently are slightly darker and more yellowish-orange on fresh and weathered surfaces, respectively.

Sedimentary structures such as burrows, mudcracks, scours or small channels, and fenestral cavities are especially abundant in this laminated lithofacies (Fig. 2.2). Scours and small channels are frequently filled by laminated sediments. Ripples and cross-bedding rarely occur. Diagenetic structures, such as chert and carbonate nodular pseudomorphs of evaporites, solution-collapse breccias, stylolites, and quartz or carbonate veins are also common (Fig. 2.2). The characteristics of laminae are discussed below. (For details on the other structures see chapters 3 and 4.)

Laminations usually are discernible by their differential resistance to weathering or by the alternation of lighter and darker bands on fresh and weathered surfaces (Figs. 2.4C,D, 2.6, and 2.7). Laminae generally are planar or slightly undulating to occasionally discontinuous and show frequent small corrugations and irregularities in thickness. They commonly are less than 5 mm thick. Laminated dolostones may be composed of a continuous succession of vertically-stacked laminae (Fig. 2.5) or as laminated horizons separated by mottled or, more rarely, homogeneous segments (Fig. 2.4C,D) defining thinly or moderately to widely spaced laminated rocks, respectively. These horizons may be up to 5 cm thick or more. Laminated horizons may consist of one or several laminae.

Occasionally, similar but convex-upward laminations form domes (or hemispheroids). The domes usually are isolated or separated by a few meters with linkage by planar laminations (Fig. 2.6). Their height and length usually is less than 10 cm and 20 cm, respectively. Well-developed laterally-linked hemispheroids (LLH-C structures of Logan and others, 1964) have been observed very close to the base of the formation at the Providence Island Section, Vermont (9.2.10) (Fig. 2.7). These have an average height and length of 3.5 cm and 8.5 cm, respectively. Smaller laterally-linked hemispheroids (LLH-C) occur at the Granville Public Fishing Site section, New York (9.2.10) where they carpet a surface which became mudcraked and then eroded (Fig. 2.9). Their internal structure consists of an alternating reddish and very pale orange colored laminae on the weathered surface. The variability in color is probably due to concentrations of oxidized fine grained pyrite crystals within the reddish colored laminae. Such pyritic concentrations are common within a particular laminae type (CPA type, discussed below). Occasionally, it is observed that the cores of the domal stromatolites rest on structures with relief which represent small domes, ripples, or ridges (shaped by erosion) in the underlying sediments (Fig. 2.7). Most of the domal stromatolites are slightly to moderately asymmetrical with one side steeper than the other (Figs. 2.6 and 2.7). At the outcrop of Providence Island, Vermont (9.2.10), a domal stromatolite, elongated approximately in an east-west direction, has been observed at about 8 m from the base of the section (Figs. 2.6 and 9.27). This observation may indicate that some or most of the domes could represent elongated structures. The laminae of some domal stromatolites are broken and form flat fragments which commonly collect in associated scours or small channels (3.3) (Figs. 2.10A,B). Domal stromatolites may persist through a bed and define the elongate domal structure on its top (Fig. 2.6).

The minerals and particles of the laminae are almost identical to those of mottled dolostones. However, some aspects of the fabric and the relative proportion of components differ between the laminae, especially between those having a strong color contrast (Fig. 2.4C,D). Based on these two variables, most laminae in dolomitic rocks belong to two major groups:

Type I: FM-CPA alternating laminae (Fig. 2.4C,D). The notation FM symbolizes fine grained (F), and matrix (M), whereas CPA stands for coarse grained (C), pyrite crystals (P), and allochemical-terrigenous (A).

Type II: F-CA alternating laminae (Fig. 2.5). In contrast to type I laminae, the content of matrix or pyrite crystals is insignificant in F or CA type laminae, respectively.

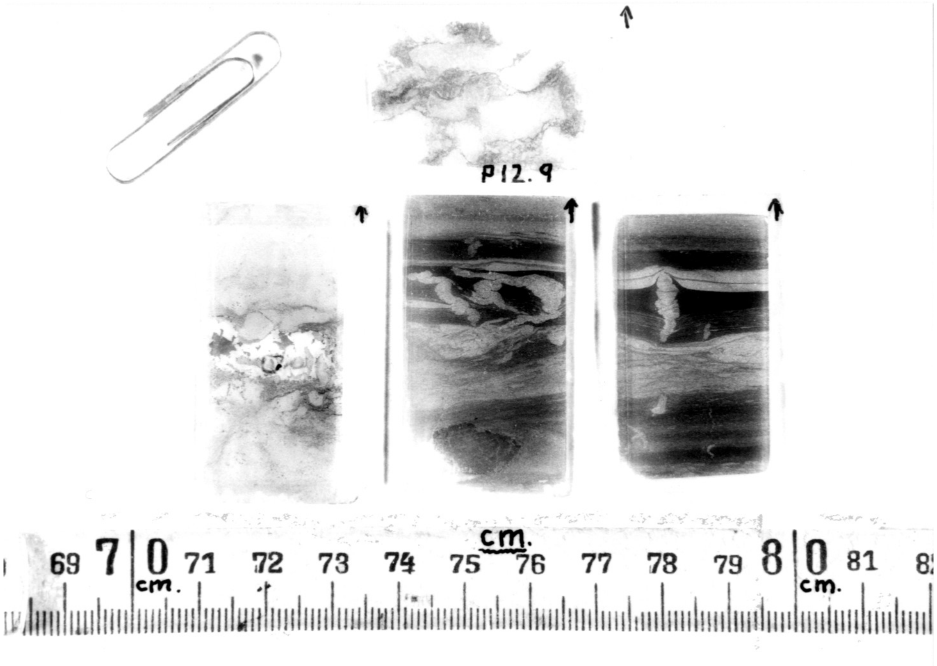

Fig. 2.4.- Stained thin-sections. A) (top) Solution-collapse breccia with a dedolomitic matrix (dark). Clasts consist of pelbiomicrites containing peloids (possibly micritized grains) and pockets of sparite surrounded by micritic envelopes. Note that the clasts show stylolitic margins. Providence Island Section (5.5 m). B) (bottom left) Calcite-dolomite nodule (center) in mottled dolostone. Note that dolomite (light) lines the outer margin of the nodule whereas calcite (dark) is restricted to the core. Saranac River Section (1.75 m). C-D) (bottom center-right) Burrowed laminated dolostone illustrating FM (dark) and CPA (light) type alternating laminae, vertical burrow (about center left; D) serving as a differential compaction marker, and calcite nodule (bottom; C). Saranac River Section (3.25 m) Arrow indicates top in all the photographs.

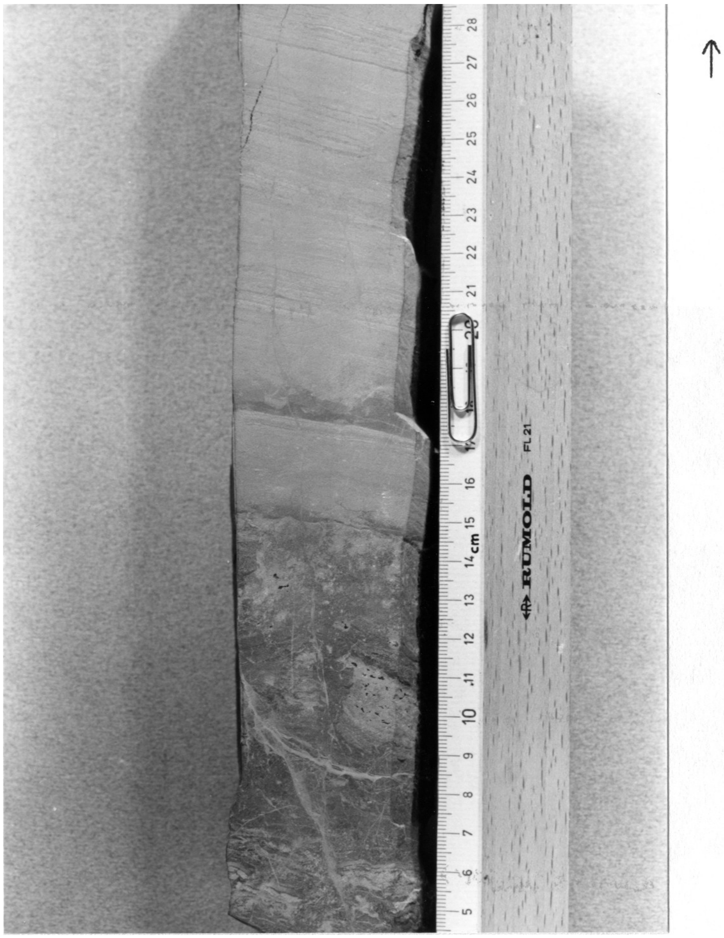

Fig. 2.5.- Polished and etched slab of dolostone showing a "shallowing-up" sequence. Note mottled (below; lower intertidal) and mudcracked laminated (above; upper intertidal) facies. Mudcracks appear as laminae discontinuities. Isle La Motte Section (18.5 m). Arrow indicates top.

Fig. 2.6.- Dolostone bed showing planar and domal stromatolites from Providence Island Section (8.2 m).

Fig. 2.7.- Hand specimen illustrating a laterally-linked hemispheroid. Note that the core is resting on structure with relief in the center of the photograph (compare with Fig. 2.8). Some burrows are present (high relief, e.g. to the left below the center). Providence Island Section (loose fragment; 3.75 m ?).

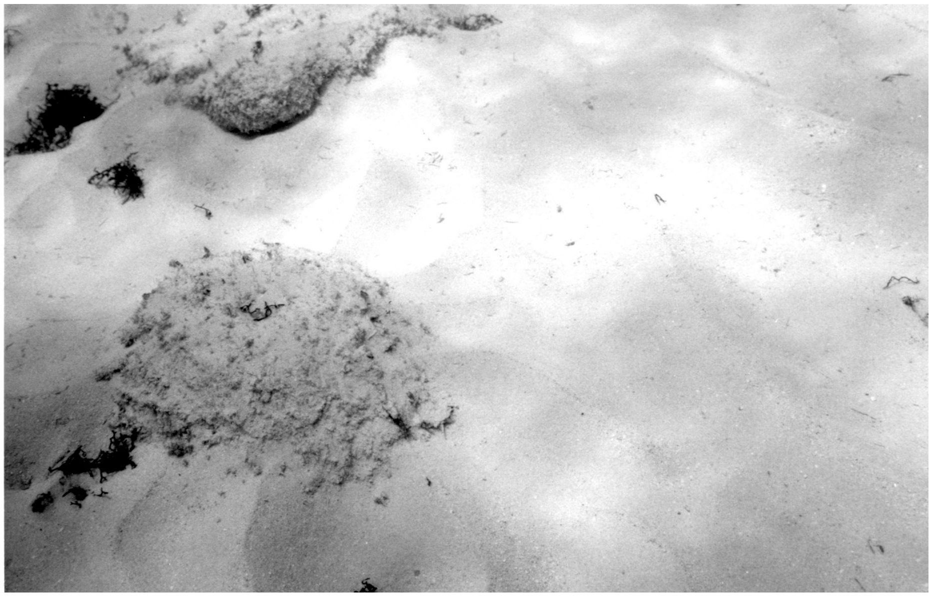

Fig. 2.8.- Sub-circular domal stromatolite, 45 cm in average diameter, in 5 m of water. Note its development on rippled surface (compare with Fig. 2.7). Whale Bay, Bermuda.

Fig. 2.9.- Plan view of dolostone bed illustrating mudcracked laterally-linked hemispheroids. The top of the bed has been partially eroded and reveals the internal structure of the domes. Granville Public Fishing Site Section (3.2 m). Scale is in cm.

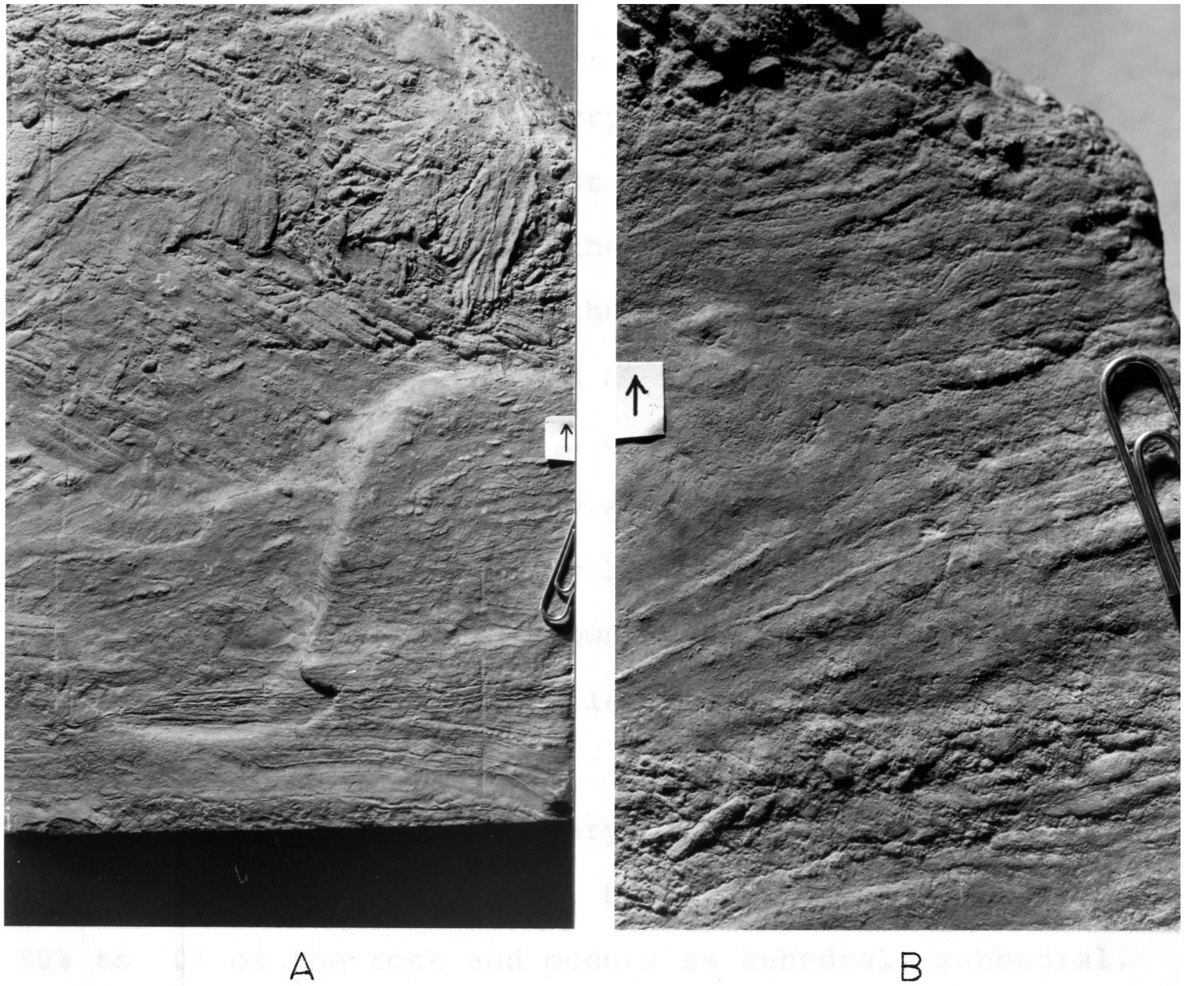

Fig. 2.10.- A) Hand specimen of dolostone showing domal stromatolite with broken laminae. B) Portion of the same sample. Note that some of the eroded "flat-algal intraclasts" are deposited in associated scours. Isle La Motte Section (12.6 m).

Type I:

FM laminae vary in color from dark gray (N3) to grayish black (N2). Dolomite constitutes about 85% of the rock and occurs as 15 um to 35 um euhedral, subhedral, and, rarely, anhedral crystals (Fig. 2.11). Their textural considerations are the same as for similar crystals in mottled dolostones. The matrix represents the rest (15%) of the rock and, as well as for the matrices of the other types of laminae, is almost identical to that of the dark mottles of mottled dolostones (2.3). Terrigenous material, relatively large pyrite crystals and allochems occur only in trace amounts. Quartz and pyrite are usually angular and subhedral, respectively, and are roughly 10 um in size. Pellets occur as irregular, ovoid, dark brown particles, about 20 um to 25 um in size and are slightly flattened and sub-parallel to bedding.

CPA laminae generally vary in color from medium light gray (N6) to light gray (N7). Dolomite generally represents 60% to 70% of the rock and occurs as euhedral, subhedral, and, more rarely, anhedral crystals ranging from 55 um to 90 um in size (Fig. 2.12). Relatively large pyrite crystals are euhedral or subhedral and comprise 5% to 20% of the rock. Their grain size is quite variable, generally ranging from 10 um to 200 um with the most common value being near 50 um. As in homogeneous or mottled dolostones (2.3), pyrite may appear as inclusions within the dolomite rhombs or occur as an intergranular phase (Fig. 2.12). Detrital quartz account for 10% to 20% of the rock and occurs as angular, equidimensional and, more rarely, elongated clear grains 30 um to 75 um in size. Occasionally, quartz composes overgrowths that drape the sub-angular to sub-rounded cores of detrital quartz. Such overgrowths have not been observed much in the other lithofacies. Muscovite, feldspars, zircon, and tourmaline are minor accesory detrital phases (Fig. 2.3). Skeletal fragments mostly occur in CPA laminae, in concentrations not exceeding 0.5%. They are identical to those found in mottled dolostones. Some fossil fragments seem to have been micritized (Fig. 2.12). Peloids, mostly pellets, rarely exceed 3% of the rock. However, they may be especially abundant in associated scour- or channel-fill deposits (3.3). More irregularly shaped peloids appear to be particles with a micrite envelope or are completely micritized grains (Fig. 2.12). The intergranular material of CPA laminae contains generally 5% or less matrix material and a similar amount of iron poor calcite and ferroan dolomite. The latter phases occur as anhedral crystals generally ranging from 10 um to 30 um in size.

Type II:

F laminae, in contrast to FM laminae, are finer grained and have a wider color range on the fresh surface; these colors vary from medium light gray (N6) to grayish black (N2). Dolomite represents about 95% or more of the rock and usually occurs as subhedral crystals about 5 um in size. Dark brown matrix material rarely exceeds 1% with the

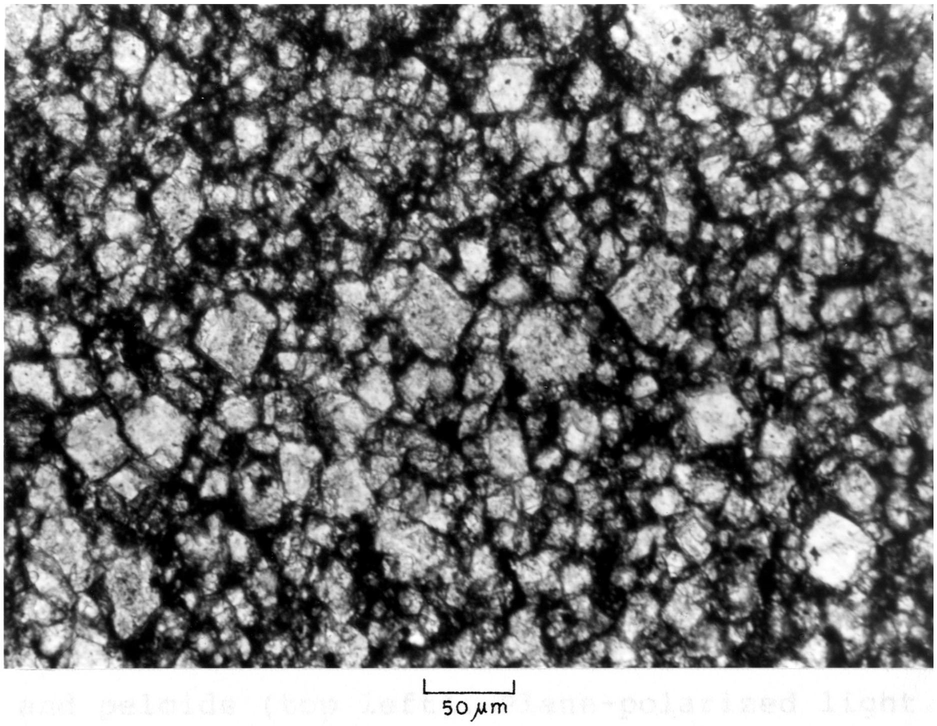

Fig. 2.11.- Photomicrograph of FM type laminae. Note euhedral or subhedral cloudy dolomite rhombs where crystals are isolated or intersecting each other, respectively. Some of the larger crystals are distinctly zoned (e.g. left of center). The zoning is probably due mainly to varying amounts of matrix-material incorporated in the growing crystals. Commonly, homogeneous and mottled dolostones show similar compositional and textural considerations. Plane-polarized light. Saranac River Section (3.25 m).

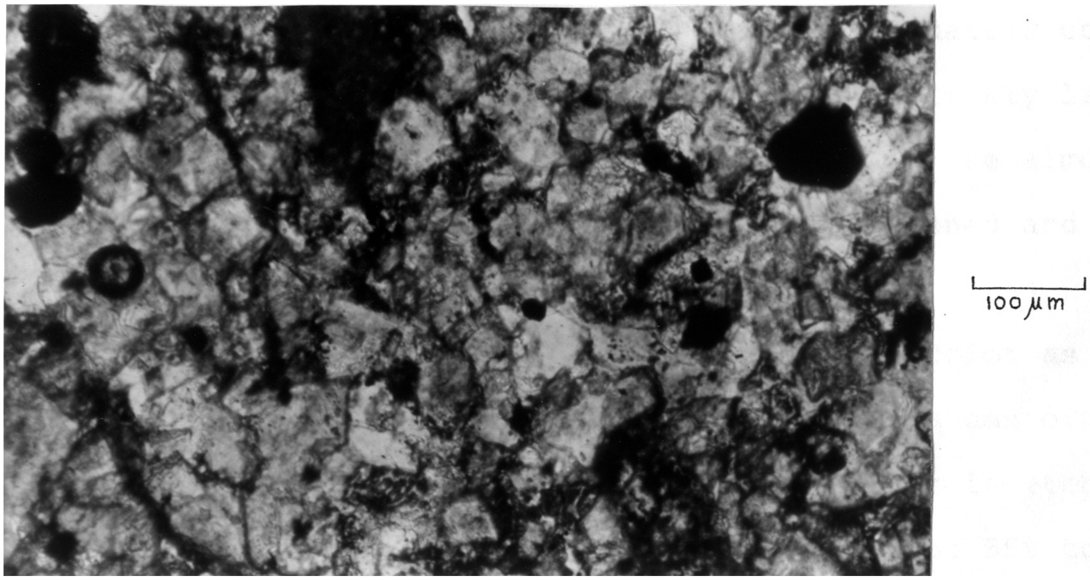

Fig. 2.12.- Photomicrograph of CPA type laminae. Although the texture is interlocking the rhombic shape of many dolomite crystals is outlined by the zoning. Note the presence of pyrite crystals (e.g. upper right), quartz grains (e.g. the clear, low relief grain below of center), possible micritized fossil fragments (lower left hand corner) and peloids (top left). Plane-polarized light. Saranac River Section (3.25 m).

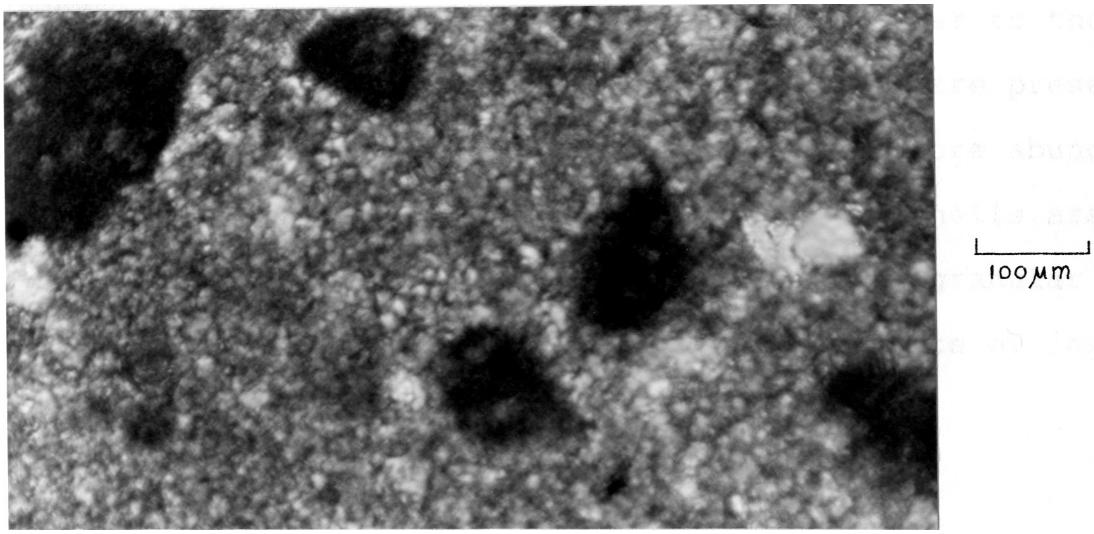

Fig. 2.13.- Photomicrograph illustrating pellets in CA type laminae. Plane-polarized light. Isle La Motte Section (0.25 m).

exception of occasional sub-laminae where the matrix content is slightly higher. Terrigenous material, relatively large pyrite crystals, fossil fragments, and pellets are almost absent. The latter commonly are slightly flattened and sub-parallel to bedding.

CA laminae commonly show almost the same color as the associated F laminae. These alternating laminae can often be observed only in extensively weathered rocks or in etched, polished rock slabs (Fig. 2.5). CA contain about 55% to 75% of dolomite crystals that are mostly subhedral. These crystals generally range in size from 15 um to 60 um. Terrigenous material commonly represents quartz grains (2-10%) and minor amounts of muscovite, feldspars, tourmaline, and zircon (Fig. 2.1). Pyrite crystals, about 20 um in size, rarely exceed 2% of the rock. Peloids, mostly pellets, occur in about the same proportions as quartz and range from 20 um to 3 mm in size. They show little evidence of flattening (Fig. 2.13). Traces of fossil fragments, similar to those existing in CPA laminae or mottled dolostones are present. However, ostracod shells seem to be slightly more abundant in this type of laminae. Occasionally, these shells are articulated. The intergranular matrix or intergranular coarse grained phases, such as iron poor calcite or ferroan dolomite, rarely exceeds 2% of the rock.

Interpretation

It is proposed that most or, perhaps, all laminated dolostones represent stromatolites. Several lines of evidence support an algal origin for the laminae. Their corrugations, discontinuities, and irregularities in thickness serve to distinguish them from even, continuous laminae formed by physical processes (Tucker, 1984). The laminae occasionally form characteristic arched stromatolitic domes that suggest that the planar laminae with which they are associated with are also of algal origin (Fig. 2.6). The presence of planar fenestral cavities or "birdseyes" is characteristic of algal produced laminations (3.5) (Shinn, 1983). The association of laminae with mudcracks and evaporites, the latter mostly replaced by chert and carbonate (4.1), is also characteristic of algal mat facies of modern arid-semiarid carbonate tidal flats (Bathurst, 1975). In view of the fact that mottled and a few homogeneous facies have been deposited in the lower intertidal and supratidal zones, respectively, of the tidal flats (2.3), it is thought that the laminated (algal) facies are restricted to the upper intertidal zone where high salinities prevent the occurrence of burrowing and browsing organisms (2.3) (Fig. 2.2). This interpretation is consistent with the common distribution of algal facies in the upper intertidal portion of modern arid-semiarid carbonate tidal flat settings where the existence of hypersaline conditions exclude such grazing organisms as gastropods (James, 1984). The presence of burrows, as well as intercalations of mottled horizons in the laminated dolostones may reflect small sporadic floodings which normalized the salinity and thus enable burrowing organisms to colonize temporarily the upper intertidal zone. Restricted marine conditions in the depositional environment are inferred by the presence of planar stromatolites (Kendall and Skipwith, 1968b; Tucker, 1984) (7.1).

The study of modern stromatolites has shown that trapping and binding of lime mud and other sediment particles are the most important mechanisms by which algal stromatolites are built (Gebelain, 1969; Bathurst, 1975), However, some of the carbonate material may have precipitated onto the algal mats by processes associated with photosynthesis of blue-green algae, sulfate-reduction within the mats and/or decay of algal tissue (Owen and Friedman, 1984).

The morphology of stromatolites depends on several environmental factors. The most important probably are current velocity, rates of sediment movement over the bottom, and frequency of exposure (Gebelain, 1969; Tucker, 1984). Domal stromatolites are thought to occupy the seaward fringe of the algal facies. This area is more often covered by water and, therefore, subject to conditions of higher turbulence and higher rates of sediment movement and supply (Hoffman, 1976; Gebelain, 1969) (Fig. 2.2). The presence of flat algal intraclasts within certain domal stromatolites and associated scours may be evidence of water turbulence as well as of early partial lithification or high cohesiveness of the mats (5.1). However, planar stromatolites probably dominate the landward fringe of the algal facies which is less covered by water and hence, subject to more restricted marine conditions (Hoffman, 1976) (Fig. 2.2).

Domal stromatolites appear to develop preferentially on surfaces with relief; this conclusion is based on the structures found in some of their cores (Fig. 2.7). A similar association exists in modern settings which have been observed by this author in Bermuda (Fig. 2.8) and reported by Gebelain (1969) and Hoffman (1976). In view of the fact that domal stromatolites are elongated and oriented frequently normal to the shoreline (Hoffman, 1976) or in the direction of predominant water movement (Gebelain, 1969), it is thought that the approximate east-west elongation of a domal stromatolite found at the Providence Island section (above; 9.2.10) indicates that the local orientation of the shoreline is approximately north-south (7.1). The asymmetry shown by some domal structures probably reflects an asymmetrical sediment supply (Gebelain, 1969) where the steeper side faces the area of higher sediment supply.

The origin for the two types of alternating laminae is uncertain. A possible interpretation is that finer (FM or F) and coarser (CPA or CD') grained laminae possibly are related to tidal motions and, especially, storm floodings.

This interpretation is based on personal observations in Long Bay, Bermuda, where lime mud is trapped and stabilized by sea-grass. During storms, the water contains large concentrations of mud and organic material in suspension. Significant amounts of organic debris, including skeletal fragments, are deposited on the beaches during storms. It takes a few days until the suspended sediments settle on the bottom. In addition, the storms are often accompanied by strong winds which transport to the subtidal environment large amounts of particles from beaches or exposed Pleistocene eolianites. Therefore, it is thought that CPA laminae, which contain high concentrations of terrigenous material (probably aeolian in origin; 2.11), pyrite (associated with organic matter content; 5.2) and, to a lesser extent, skeletal fragments may reflect a similar storm event. In the time following the storm, the mud and organic matter, still in suspension, are washed across the mats by tidal currents, where they are trapped and bound by algae to form FM type laminae. Thus, this mechanism may explain the association of FM and CPA laminae. The alternating of F and CA laminae may reflect a similar mechanism although the magnitude of the storm is possibly much smaller since CA laminae have a lower content of terrigenous material and pyrite. Analogous storms to those of Bermuda have been widely reported in other modern carbonate environments, including tidal flats (Shinn, 1983).

2.5 Homogeneous limestone

Based on the same reasons given for homogeneous dolostones, this lithofacies will be discussed jointly with mottled limestones.

2.6 Mottled limestone

Description

The limestones of this lithofacies are primarily fine-grained rocks that are mainly characterized by the presence of mottled structures (discussed below). The bedding thicknesses and rock colors on fresh or weathered surface are comparable to mottled dolostones (Figs. 9.17 to 9.33). However, mottled limestones, as well as the other calcareous lithofacies, more frequently show a pinkish gray (5 YR 8/1) or yellowish gray (5 Y 8/1) color on the weathered surface than the dolomitic facies. Mottled limestones are generally restricted to the calcareous members of the Providence Island Formation although this facies occurs interbedded with the dolomitic lithofacies.

As in mottled dolostones, sedimentary features in this lithofacies are mottling and, to a lesser extent, mudcracks, scours, and small channels, intraclasts, and fenestral cavities. Diagenetic structures frequently include stylolites and certain white quartz and carbonate veins. Diagenetic nodules are very scarce and solution-collapse breccias have not been observed. Mottling is characterized by the presence of different colored, irregularly shaped areas (mottles) on fresh and weathered surface. Lighter areas are coarser grained, more detrital, and skeletal-rich whereas darker areas have a higher content of matrix material. The relative proportions of these components are comparable to those in their dolomitic counterparts. For details on the other structures see chapters 3 and 4.

Calcite crystals represent between 50% and 95% of the rock and commonly occur as micrite-microspar or as a mosaic of anhedral crystals (spar) ranging in size from 10 um, or less, to 50 um. This type of fabric defines an allotriomorphic texture for the rock. The rest of the rock is composed of variable amounts of dolomite, terrigenous material, fossil fragments, pellets, and dolomitic intergranular matrix. The textural features of the non-calcitic constituents are very similar to those of mottled dolostones. The concentration of dolomite is variable and ranges from 5% or less to up to 50% or more in the dolomitic varieties. The dolomite rhombs frequently appear to form aggregates which are often surrounded by detrital material. As in mottled dolostones, the terrigenous material is mostly represented by quartz and minor amounts of muscovite, K-feldspar, plagioclase, tourmaline, and zircon. In contrast to dolomitic rocks, fossil fragments are more common in this lithofacies and occur as isolated fragments (5-10%) or are concentrated in small areas to form pockets, thin discontinuous laminae, or small lenses. The fragments, especially ostracod shells, are often silicified. The skeletal particles are identical to those in skeletal limestones (chapter 2.8) or grainstone intercalations within the dolomitic rocks (2.3 and 2.4). The pellets are micritic and occasionally may represent 5% of the rock.

The intergranular matrix resembles that of dolomitic rocks. The relative proportions of carbonate and non-carbonate phases are similar. However, the carbonate portion in the mottled limestones consists mainly of micrite or microspar instead of microcrystalline dolomite. The non-carbonate phases appear to be the same. Dolomite rhombs are very prominent in matrix-rich areas or horizons.

Interpretation

Micrite is thought to represent a lime mud that has been subsequently lithified (Folk, 1965; Wilson, 1975). Coarser calcite crystals in this facies possibly represent a neomorphic replacement of micrite (Bathurst, 1975). The environmental interpretation for homogeneous or mottled limestones seems likely to be the same as for homogeneous or mottled dolostones due to the presence of similar features in these lithofacies. The fact that fossil fragments are more common in this than in dolomitic dolostones is probably due to their preservation from dolomitization processes. This interpretation is supported by the presence of altered fossil fragments in dolomitic rocks (2.3). Therefore, it is proposed that most homogeneous and mottled limestones represent lower intertidal deposits (Fig. 2.2). In contrast to the interpretation of certain homogeneous dolostones as supratidal in origin, no evidence has been found in any of the homogeneous limestones for such an interpretation.

2.7 Laminated limestones

Description.

Laminated limestones and their dolomitic counterparts are comparable in bedding thickness and in morphology of most of their laminae. The rock color is similar to that of mottled limestones. This lithofacies also contains interbedded mottled segments as well as occasional intercalations of skeletal limestones or flat-pebble conglomerates. Sedimentary and diagenetic structures are generally abundant and similar to those in laminated dolostones (2.4) (Fig. 2.2). However, a few differences concerning the frequency of these structures have been noted. This lithofacies contains fewer mudcracks and fenestral cavities (Fig. 3.12) compared to laminated dolostones. Cross-beds with laminae showing irregularities in thickness have been noted in this lithofacies (3.4) (Fig. 3.10). Solution-collapse breccias have not been observed, although they may exist. For details on the description and interpretation of these structures see chapters 3 and 4. Planar laminations are the only laminae type that have been observed in this lithofacies and are similar in morphology to those of laminated dolostones. The different types of alternating laminae present in dolomitic facies are also represented in this lithofacies. However, the nomenclature used for the calcitic laminae differs slightly from the dolomitic laminae due to compositional differences. Most calcitic laminae belong to two major groups:

Type I: Mc-SPA alternating laminae (equivalent to type I of dolomitic laminae): The notation Mc symbolizes micrite, whereas SPA stands for sparite (S), pyrite crystals (P) and allochemical-terrigenous (and dolomitic) material (A).

Type II: Mc-SA alternating laminae (equivalent ot type II of dolomitic laminae): In contrast to SPA laminae (type I) the content of pyrite crystals is insignificant in SA laminae.

This classification is tentatively suggested because fewer specimens have been observed and compared to one another.

Mc type laminae are composed of micrite with trace to small amounts of accesory material such as dolomite, pyrite, terrigenous material, pellets and fossil fragments. The latter, especially ostracod shells, are frequently replaced by silica and are often sub-parallel to the laminae surfaces. SPA or SA laminae consist of neomorphic spar with small to significant amounts of accessory material which is identical to that found in micritic laminae. Occasionally, the laminae are almost entirely composed of fossil fragments similar to those in skeletal limestones (2.8) or grainstone intercalations in the other dolomitic or calcareous lithofacies. Terrigenous material in SPA or SA type laminae occasionally represent 30% of the rock or more. Calcitic laminae frequently alternate with dolomitic laminae. In such cases, laminae are easily recognized by their differential weathering because dolomitic laminae show a higher relief than the calcitic laminae (Fig. 2.14). Commonly the observed dolomitic laminae are of the FM type (2.4). These laminae generally are composed of 60% to 90% euhedral to subhedral dolomite crystals, 10 um to 70 um in size, that float in a dark brown dolomitic matrix. This matrix is sometimes partially micritic.

Skeletal limestones are frequently laminated. However, in many instances they do not show any evidence of lamination and hence, this particular type of rock is discussed separately (2.8).

Interpretation

It is proposed that the laminated character of this lithofacies is mostly due to the presence of stromatolites which developed in the upper intertidal zone of the tidal flats. This interpretation is supported by both the close association of the laminae with planar fenestral cavities (3.5) (Fig. 3.12) and the similarities that exist with laminated dolostones (described above) which reflect stromatolitic deposition in such an environment. Some or many of the dolomitic laminae occurring in this lithofacies possibly have formed by selective replacement of magnesium-

Fig. 2.14.- Hand specimen illustrating burrowed calcitic-dolomitic alternating laminae. Calcitic laminae (Mc type) is darker and shows a lower relief than dolomitic laminae (CPA type). Note calcareous intraclasts at the top of the specimen. Isle La Motte Section (0.75 m).

rich algal mats which were interbedded with lime mud (5.2).

2.8 Skeletal limestone

Description

The beds are commonly 20 cm to 50 cm thick although they can be as thick as 1 m. Bedding often consists of normally graded skeletal limestone horizons that alternate with mottled and laminated dolostones or, less commonly, any of the other previous lithofacies (Fig. 2.16). The color range of skeletal limestones is similar to that shown in mottled or laminated limestones (Figs. 9.17 to 9.33). The diversity of the biota seems to be relatively low. Fossil fragments generally are abraded and include brachiopods (linguloids), trilobites, gastropods, pelmatozoans, ostracods, calcareous algae, and nautiloids (Fig. 2.15). The relative proportions of the fragments are variable. Some beds consist almost entirely of pelmatozoan plates while others consist of ostracod shells or other skeletal types. Ostracod shells are frequently articulated and occasionally are replaced by silica. Dasycladaceae fragments have been identified by E. Landing. The inner shell margin of certain unidentified, micrite filled, tube-like skeletal fragments have been replaced by prismatic quartz crystals, whereas the outer margin consists of a thin calcite fringe. It appears that as the micrite content of the rock increases the silicification of the skeletal fragments becomes more prominent. Micritized skeletal fragments frequently occur.

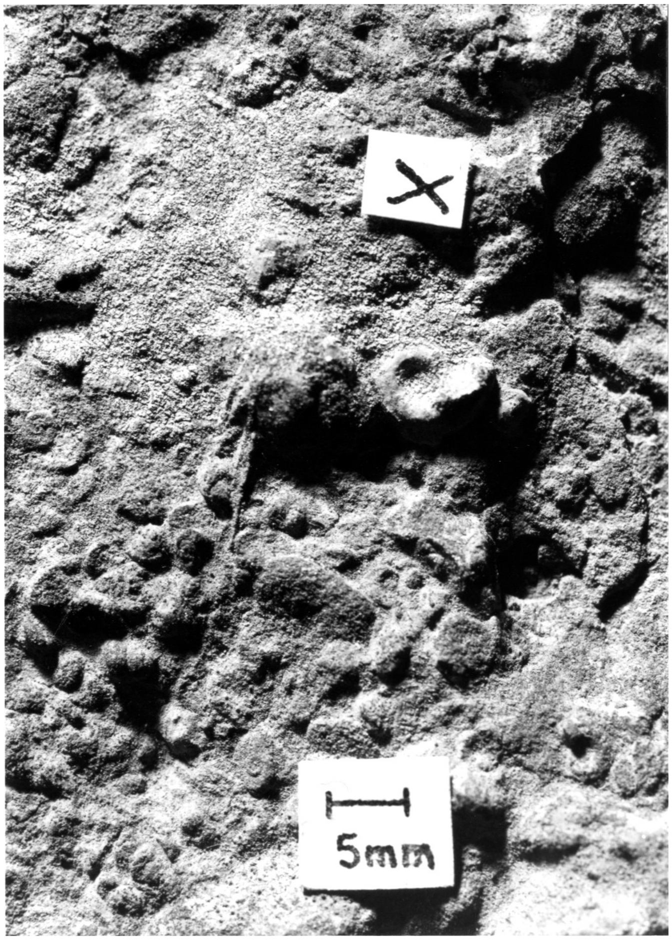

Fig. 2.15.- Plan view of top of bed of a skeletal limestone (storm deposit). It consists of abraded fossil fragments and intraclasts of various sizes. Isle La Motte Section (2.75 m). "X" symbolizes top surface.

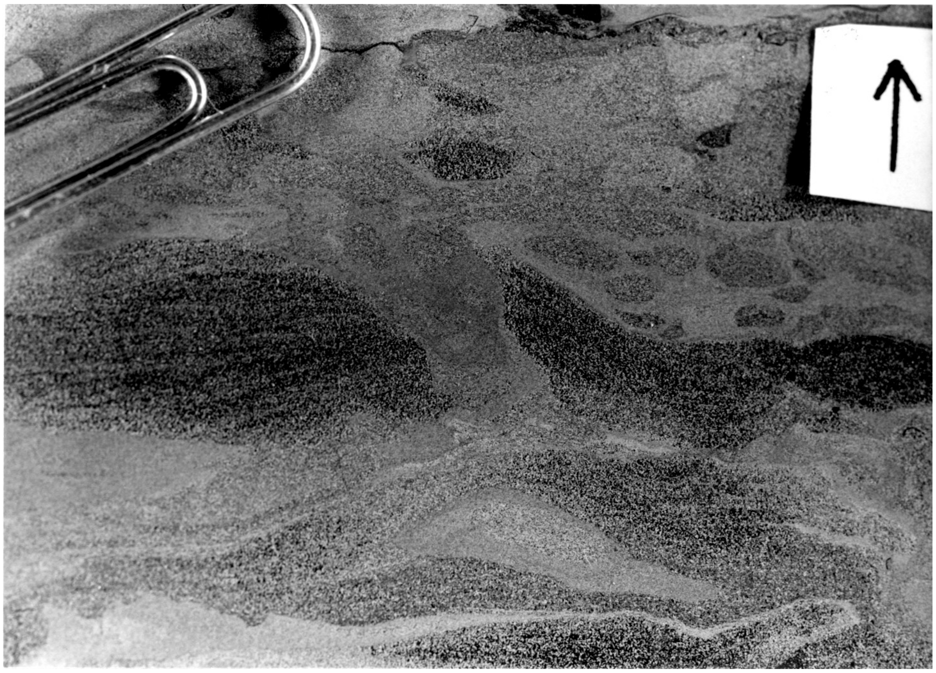

Fig. 2.16.- Polished and etched slab of burrowed laminated skeletal limestone. Burrows and associated mottled facies (by the arrow) are dolomitic. Town Farm Bay Section (6.5 m). Arrow indicates top.

Intraclasts are widely distributed although their concentration rarely exceeds 5%. They may be abundant locally, as in the Boss Hogg's Quarry, West Haven, Vermont (3.3 and 9.2.4). The lithoclasts usually consist of fragments of homogeneous, mottled, or laminated limestones. Further details on intraclasts are presented in chapter 3.3. Terrigenous material commonly represents 5% to 15% of the rock. The terrigenous components, as well as their relative proportions are similar to those occurring in dolomitic facies (Fig. 2.3). However, in certain beds, the quartz to feldspar ratio may be 2:1. Pellets are commonly found although in concentrations less than 1%. Pellets and pyrite crystals often appear in association.

The micrite is generally turbid due to very finely disseminated pyrite, carbonaceous material, and clays(?). The concentration of micrite varies between 1% or less in grainstones and to 60% or more in wackestones. Calcite-spar appears as equigranular mosaics that usually represent less than 5% of the rock. Skeletal grains occasionally are preserved by calcite-spar. Large single calcite crystals occasionally include detrital calcite grains. This suggests a syntaxial overgrowth of calcite over fossil pelmatozoan plates. Dolomite rhombs occur disseminated in micrite or sparite in concentrations usually between 1% and 6%. The rhombs generally contain euhedral ferroan cores and are very similar to those described in mottled dolostones. Euhedral, authigenic quartz and quartz after calcite may occasionally occur and frequently show abundant inclusions.

A few burrows, scours, ripples, and cross-laminae have been observed (Fig. 2.16). Burrows commonly penetrate the underlying skeletal interbeds in mottled horizons (Fig. 2.16). Burrows and mottled horizons are of comparable composition. Diagenetic structures are very uncommon, except for occasional stylolites. For detailed information on these structures see chapters 3 and 4.

Interpretation

It is proposed that these sediments reflect storm deposits. This interpretation is based on the presence of abraded grains which probably indicate wave action in shallow water (Wilson, 1975) and on the occurrence of analogous modern deposits consisting of subtidal, skeletal and pelletal grains transported onto the tidal flats during storm surges (Friedman and Sanders, 1978). The relative low diversity of the biota may indicate restricted marine conditions for the adjacent subtidal environment (Wilson, 1975) and, therefore, for the tidal flats. The presence of bioclastic grainstone intercalations in any of the previously discussed tidal flat lithofacies suggests that skeletal limestones can be located anywhere within the tidal flat (Fig. 2.2). However, these thin storm lags may have been better preserved in the upper intertidal-supratidal environment because burrowing did not disrupt and mix these layers into underlying sediments (Shinn, 1983). Some fragments may have been abraded during the burrowing activity (Moore and others, 1952). The particle-to-micrite ratio is probably directly proportional to the degree of agitation.

The frequent irregularities in thickness of some of the laminae probably reflect the presence of algal mats (2.4) and, perhaps, microstylolites (4.4). Gebelain (1969) has observed in subtidal algal mat facies of Bermuda that storm deposits are bound by the filaments of the algal mats covered by such deposits.

Silicification and stylolitization mechanisms are discussed in chapters 5.4 and 5.6, respectively.

2.9 Dedolostone

Description

Dedolostones occur as beds up to 1 m thick or as areas or horizons intercalated between the thicker bedded dolostones. The rock color is usually medium dark gray (N5) and grayish orange (10 YR 7/4) on the fresh and weathered surface, respectively. This lithofacies is well represented only at Providence Island, Vermont (9.2.10), where it occurs in association with dolostones as well as nodular chert, chert-calcite nodules, bedded chert, solution-collapse breccias, and, to a lesser extent, stylolites. Fenestral cavities are the only primary sedimentary structures that have been observed in this lithofacies. For details on these sedimentary and diagenetic features see chapters 3.5, 4.1.1, 4.2, and 4.5.

Dedolomite (calcite replacement of dolomite) usually represents between 30% and 70% of the rock and occurs as euhedral or subhedral rhombohedral crystals that range in size from 60 um to 500 um and commonly average 100 um. Micron-size voids are commonly observed within the rhombs. The crystals are occasionally poikilitic and have small inclusions of pyrite, quartz, or feldspar. The rhombs may contain rare internal dolomite fringes that conform to the crystal faces (Fig. 2.17).

Dolomite usually occurs as random, slightly ferroan rhombs in concentrations ranging between 5% and 30%. The crystals are similar in shape and size to the dedolomite rhombs and are frequently zoned. Occasionally, micro- or megaquartz appears as a cementing phase.

Interpretation

The dolomite shape of the dedolomite crystals as well as the occasional presence of dolomite fringes within the dedolomite rhombs suggests that dedolomite has resulted from the replacement of dolomite by calcite. This process called dedolomitization seems to have occurred as a result of the dissolution of evaporites which were abundant in the sediment (5.5). For this reason, it seems likely that most

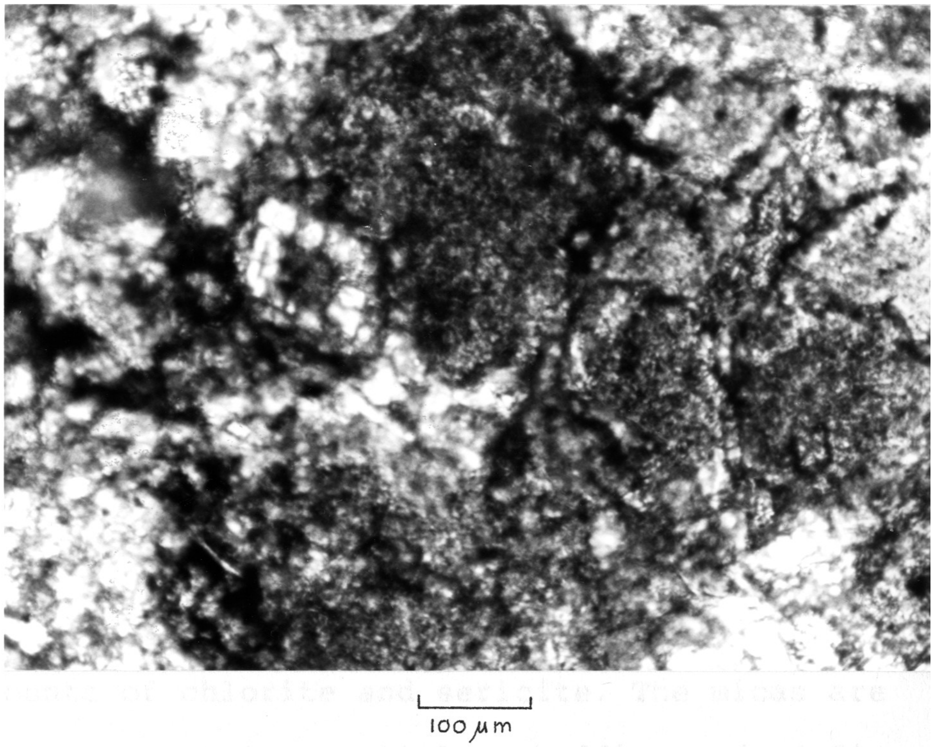

Fig. 2.17.- Photomicrograph of a stained dedolostone. Note that one of the dedolomite rhombs (dark) contains a clear internal dedolomite fringe (light) which conform to the crystal faces. Plane-polarized light. Providence Island Section (5.25 m).

of the original sediments are supratidal in origin (Fig. 2.2).

2.10 Shale

Description

Shale occurs as partings or easily cleaved beds that are less than 5 cm thick and which are interbedded with the dolostones or limestones. Its color generally is grayish black (N2) to medium dark gray (N4) in fresh and dry weathered surface, respectively. The partings are more easily recognized on wet surfaces. Laminations are occasionally observed. Shales appear to be more common in sections of the upper part of the formation (e.g. Isle La Motte, Vermont, 9.2.14) with occurrence increasing towards the north.

Micas and clays, 1-5 um in size, constitute about 70% to 90% of the rock. The mica portion is represented by about equal amounts of chlorite and sericite. The micas are oriented approximately parallel to bedding and define a lepidoblastic texture. The clay minerals are difficult to identify due to their smaller size. The mica to clay ratio is usually 2:1. Accesory components that occur in proportions between 1% and 5% include pyrite, muscovite, quartz, feldspars, and, occasionally, Fe-oxides. Components occurring in trace amounts are ferroan dolomite, zircon, and tourmaline. The terrigenous grains (except for micas and clays) as well as the dolomite crystals are ordinarily 30 um in size. Quartz grains frequently show undulouse extinction. The feldspar grains do not show evidence of hydrolysis. Pyrite crystals are variable in size and range from less than 10 um to 200 um.

In eastern rock outcrops closer to the Taconic Allochthon, the shale beds frequently are associated with thrust surfaces. In such a case, sub-horizontal calcite veins are common, showing occasionally slickensides or rotated shale fragments (Fig. 7.3).

Interpretation

Shales probably represent restricted marine tidal flat deposits based on their intimate association with dolostones and limestones which are characteristic of a tidal flat setting.

The terrigenous material is probably aeolian in origin following the lines of evidence given in chapter 2.11. Some of the dolomite crystals could be detrital due to the similarity in size to the terrigenous material (2.11). Pyrite is diagenetic in origin (5.2) and Fe-oxides probably represent final products of the oxidation of pyrite.

2.11 Note on the terrigenous constituents

As discussed on the previous chapters, the terrigenous portion of the lithofacies of the Providence Island Formation consists on variable amounts of quartz and, to a lesser extent, muscovite, K-feldspar, plagioclase, tourmaline, and zircon (Fig. 2.3). This mineral assemblage suggests that the primary rock sources probably are granites, granitic pegmatites, quartzofeldespathic gneisses, or schists and, hence, that the primary source area is the nearby Precambrian Grenville basement where these rocks are common. The absence of hydrolization in K-feldspar and plagioclase does not necessarily indicate that most of the terrigenous grains are first cycle but is consistent with an interpretation by many sedimentary petrologists that they were transported and deposited in an area subject to semiarid or arid climatic conditions (Tucker, 1984) (7.1). For this reason, these grains could alternatively have been derived in part or entirely from nearby older sedimentary formations, such as the Potsdam, Ticonderoga, or other formations, by reworking. On the basis of the lack of hydrolization of the K-feldspar and plagioclase grains and on the inferred semiaridity or aridity of the area (above and 7.1), it is thought that the main transport mechanism for the terrigenous grains is aeolian rather than aqueous. In addition, the good sorting of the terrigenous grains may also be evidence of aeolian transport. Examples of aeolian terrigenous silts in recent semiarid-arid carbonate tidal flats and adjacent subtidal environments have been documented by numerous authors (e.g. Kendall and Skipwith, 1968b; Shinn, 1983). Thus, terrigenous grains found in the laminated dolostones are probably analogous to the aeolian clastic grains in recent algal mats of the Persian Gulf which have been trapped by the sticky mucilagenous mats (Kendall and Skipwith, 1968b). The thin laminae or small lenses of terrigenous material within the carbonate sediment may reflect dust storms (Shinn, 1983). A detrital origin for some of the cloudy dolomite crystals or cores seems likely since they are similar in size to many detrital quartz grains. Such a relationship occurs between recent detrital dolomite and quartz grains in the Persian Gulf (Shinn, 1983). Part of the aeolian material probably has been subject to a later redistribution in the tidal flats by physical and biological processes (2.3). The inferred presence of aeolian grains in the lithofacies of the Providence Island Formation is very significant since it may indicate the existance of an eroding mainland in proximity to the tidal flats (7.1). Another possible mechanism of transport could be simple sediment by-passing, by which coarse grained material (sand) is left as a shore-line deposit and ambient waves and currents serve to transport clay and silt size material to the tidal flats (Landing, pers. commun., 1986).

3.- DIAGNOSTIC TIDAL FLAT SEDIMENTARY STRUCTURES

The sedimentary as well as the diagenetic structures found in dolostones and limestones are very similar. However, their description is mostly restricted to dolomitic rocks because these lithologies are the most representative of the formation. Mottling and algal laminations (stromatolites) have been previouly discussed (2.3 and 2.4). Other important structures are:

3.1 Burrows

Description

As discussed above, burrowing and browsing activities of organisms are thought to be responsible for the total or partial homogenization of homogeneous or mottled rocks (2.3). However, burrows are only easily recognized in rocks that have not been affected by extensive bioturbation. An example is laminated dolostones where the individual laminations serve as markers (Figs. 2.4C,D and 2.14).

Burrows generally occur singly, vertically, and, to a lesser extent, inclined at various angles with respect to bedding. Inclined burrows occasionally show a preferred orientation. They are commonly nearly cylindrical with dimensions ranging from less than a few millimeters to more than 8 cm in length and from less than 1 mm to about 3 cm or more in diameter. Burrows frequently cut several underlying laminae (Figs. 2.4C,D and 2.14). The infill is almost identical to the first overlying deposit, although the former is commonly slightly more terrigenous. The latter frequently corresponds to CPA or CA laminae (2.4) (Fig. 2.4C,D). Differential compaction features are common where there is a sharp compositional and textural contrast between the infill of a sub-vertical burrow and the burrowed laminae. In these cases, the walls of the burrow are commonly scalloped (Fig. 2.4D). Burrows are generally localized in particular segments within the bed without reaching underlying horizons.

Interpretation

The lack of wall lining in the burrows and the occasional occurrence of meniscate backfills suggests that some or most of the burrows represent feeding structures (Fodichnia) and/or escape structures (Fugichnia) (Frey and Pemberton, 1984). The preservation of non-lined burrows suggests that the original sediment was probably cohesive or partially cemented and hence, possibly located within the Glossifungites ichnofacies (Frey and Pemberton, 1984). Some of the burrows may represent dwelling structures since fossil fragments interpreted as belonging to linguloids have occasionally been found within the formation (2.3). This latter interpretation is supported by the presence in recent environments of linguloid brachiopods that commonly make vertical burrows in which they live (Moore and others, 1952).

The lower boundary of burrowed layers probably represents a zero-Eh surface when it lies below the sediment-water interface. Organisms commonly only burrow the upper oxygenated sediments and do not penetrate the euxinic conditions in underlying sediments. Euxinic environments are characterized by the presence of H_2S, a poisonous gas, within the sediment interstitial water (Friedman and Sanders, 1978). Because the burrowed sediments are as dark as the underlying segments, it is thought that, as the sediment accumulates, the zero-Eh surface rises, and sweeps through the bed.

3.2 Mudcracks

Description

Mudcracks are typically polygonal (Fig. 3.1) or irregularly shaped (Fig. 3.2) and occur within or on the tops of beds. Mudcracks are more obvious if they have been weathered out on bedding surfaces. Polygonally shaped cracks, the most common, occur mostly in laminated or mottled dolostones. The polygons are a few centimeters to more than a meter in diameter (Figs. 3.1, and 3.4, respectively). Finer grained laminae (e.g. FM or F types, 2.4) are more frequently broken into polygons. The cracks generally are one lamina thick and are filled by the

Fig. 3.1.- Plan view of polygonal mudcracks from Isle La Motte Section (loose dolostone fragment)

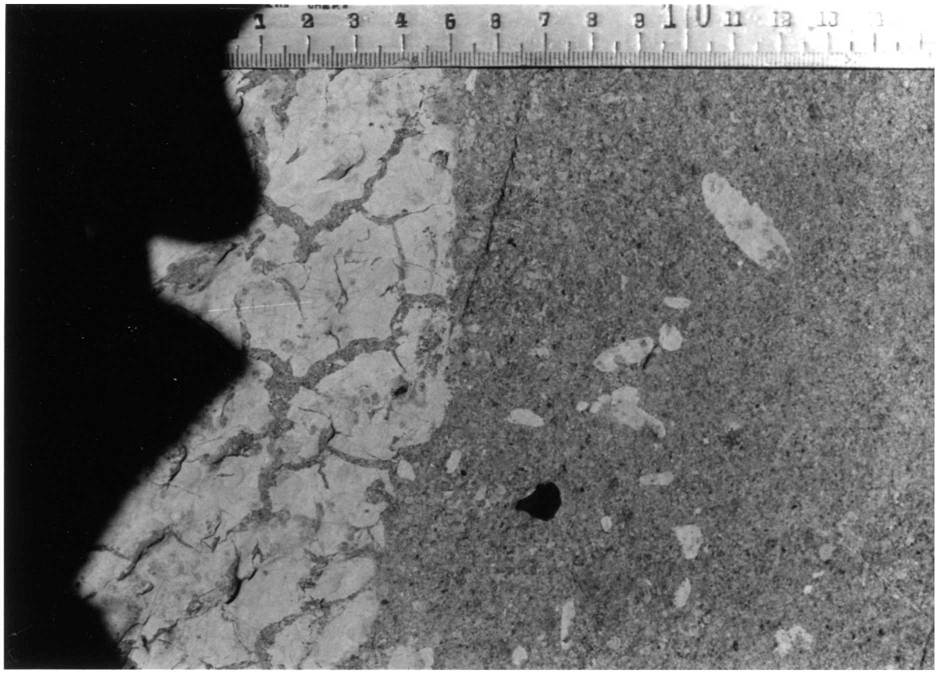

Fig. 3.2.- Plan view of irregular mudcracks in dolostone bed from Saranac River Section (2.75 m). Compare with Figure 3.3. Scale is in cm.

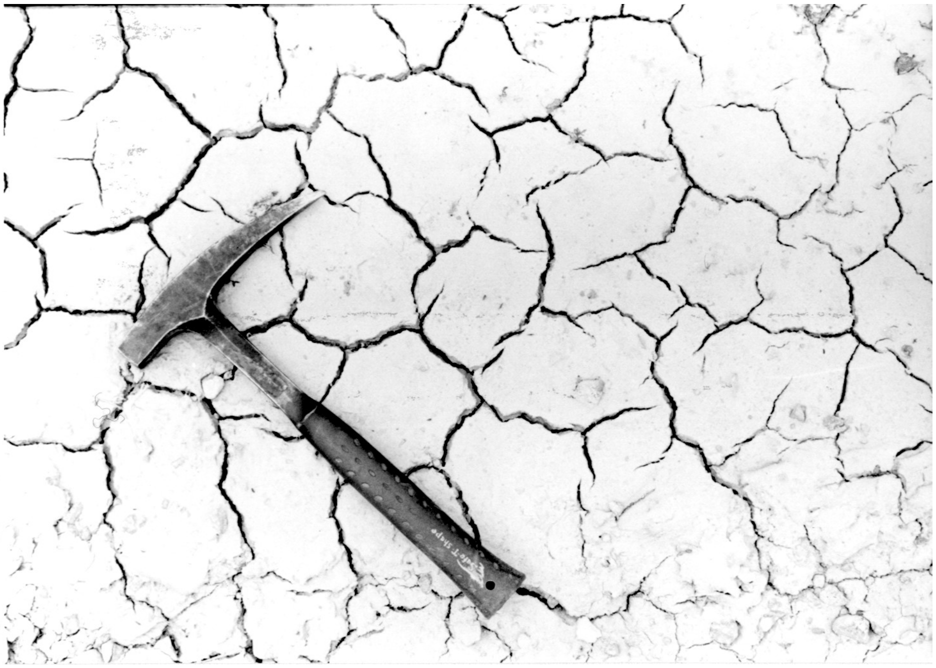

Fig. 3.3.- Plan view of recent irregular mudcracks from southern Quebec. Compare with Figure 3.2.

Fig. 3.4.- Plan view of large scale polygonal mudcracks in dolostone bed from Saranac River Section (3.5 m).

overlying material. Horizontal (bedding plane) and vertical views of the same mudcracks have been compared in order to recognize cross-sectional views of other mudcracks in beds where planar views cannot be observed. This proved to be very useful for distinguishing mudcrack- from burrow-produced discontinuities. In contrast to burrow-produced discontinuities, the compositional difference between the mudcrack fill and the laminae is not as high as for burrow fills and the laminae. Mudcrack edges are not scalloped in vertical sections, but are generally straight and sub-vertical. These edges frequently dip toward the center of the crack, but without showing a "V" shape in vertical section (Fig. 2.5).

Interpretation

Mudcracks in carbonate rocks have been commonly regarded as indicators of intertidal and supratidal settings (Shinn, 1983). They have formed by exposure, dessication, and shrinkage of carbonate mud. Irregularly shaped cracks in homogeneous or mottled lithofacies (Fig. 3.2) are thought to be mudcracks because of their striking analogy to modern, mudcracked, homogeneous clayey muds, examples of which were noted during field work (Fig. 3.3). The size of the dessication polygons probably is related to the length of subaerial exposure of the sediment (Shinn, 1983). Their preservation, as that of any primary laminations, is probably controlled by burrowing or browsing organisms.

Their near absence in homogeneous or mottled rocks is probably due to their destruction by bioturbation. Therefore, it is thought that mudcracks are mostly preserved in sediments that have been sub-aerially exposed under hypersaline conditions in which bioturbation was limited or absent. This follows since mudcracks are more commonly associated with algal laminated lithofacies which formed under hypersaline conditions (2.4). However, certain mudcracks occurring in mottled deposits that contain abundant terrigenous material may have been preserved by quick burial during storm surges.

3.3 Scours and channels. Intraclasts

Description

Scours and, to a lesser extent, channels are the most common current structures of the formation. About 80% of them occur in laminated lithofacies (Fig. 2.2). Scours are long and narrow features that range from a few millimeters to less than a meter in width and from several millimeters to several centimeters in depth. Their cross-sectional shape is variable, ranging from symmetrical to asymmetrical, and they have smooth to irregular bottoms and occasionally overhanging walls (Figs. 3.5 and 3.6). Scours generally occur on low relief, sub-horizontal erosional surfaces within or on the top or bases of the beds. This type of surface characterizes, for example, the top of the Providence Island Formation at the contact with the Head

Sandstone Member (lowest member of the Day Point Limestone) (Fig. 3.5 and 9.32).

Small channels have moderately dipping to horizontal as well as smooth to irregular profiles. These profiles are occasionally scoured (Fig. 3.6). Several scoured surfaces, whether or not part of a larger channel, may be contained within a single bed (Fig. 3.6).

The scours or channel are filled in several ways:

a) By algal mats: Initial algal laminations commonly conform approximately to the scour shape (Fig. 3.6 and 3.7). Later laminae frequently are sub-horizontal and pinch out laterally on the initial laminae (Fig. 3.7). These laminations are similar in characteristics to the surrounding laminations.

b) By intraclastic mudstones, wackestones, or grainstones: Intraclastic mudstones or wackestones are texturally similar to debris or mud flow deposits of alluvial fans. In all cases, the clasts represent consolidated to semi-consolidated fragments of surrounding lithologies such as homogeneous, mottled, or laminated dolostones or, more rarely, limestones. Different types of clasts commonly occur together (Figs. 3.6 and 3.8). The clasts are more or less equidimensional to platey, angular to sub-rounded, and range in size from less than 2 cm in scours to up to 5 cm in channels. Flattened lithoclasts are up to 3 cm long and 0.5 cm thick. The concentration of intraclasts rarely exceeds 5% of the rock. They may be very abundant locally as in the Boss Hogg's Quarry at West Haven, Vermont (9.2.4) where a 65 cm thick limestone bed consists mostly of a flat-pebble conglomerate (39 m; in Fig. 9.21). Here, as in other limestones, the clasts are frequently more dolomitic than the surrounding matrix and have a higher relief on weathered surfaces. Lithoclasts are generally poorly sorted and, especially in the intraclastic mudstones, may show reverse-grading (larger clasts overlie smaller clasts) in the lower part of the scour or channel and normal-grading at the top (Figs. 3.6 and 3.8). Smaller intraclasts may be included in larger ones (Fig. 3.8). These deposits are frequently capped by algal laminations (Fig. 3.8). The intergranular matrix is generally similar in composition and, frequently, in texture to the lithoclasts. However, the relative proportions of mineral or allochem-terrigenous constituents may differ considerably between the clasts and matrix. Pellets and fossil fragments occasionally occur in the matrix as well as in the lithoclasts. A peculiar, reddish scoriaceous weathering, 10 cm thick channel-fill deposit has been observed near the base of the formation at Providence Island, Vermont (9.2.10). It consists of a framework of dedolostone fragments ranging from 0.1 mm to 0.5 mm in diameter. These fragments occur in a laminated matrix of clastic, silica-cemented material, 15 um to 45 um in size.

c) <u>By mud</u>: Such accumulations occur mostly in scours

Fig. 3.5.- Scoured surface which defines the upper contact of the formation or post-Beekmantown unconformity at the Isle La Motte Section (25.5 m). Scours with overhanging walls probably have been modified by burrowing organisms.

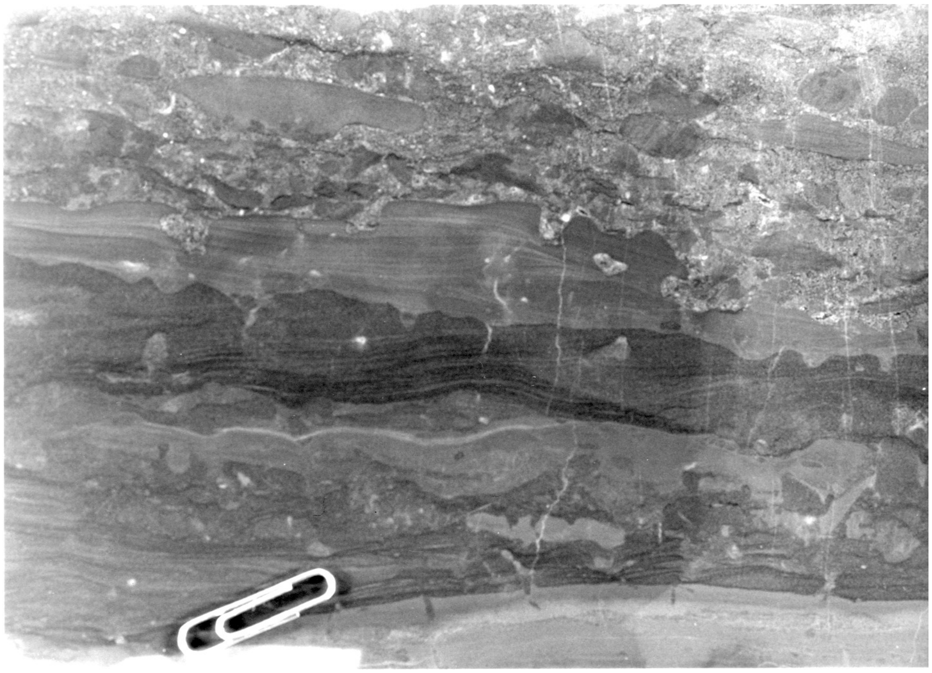

Fig. 3.6.- Polished and etched slab of dolostone showing several scoured surfaces. These surfaces probably are parts of larger channels that have been filled by algal mats (center) and intraclastic wackestones (above). Note a possible burrow-infill (just above right of center) and some scours with overhanging walls which seem to have been modified by burrowing organisms. The intraclasts are poorly sorted and show reverse and normal grading at the lower and upper part of the intraclastic channel-fill, respectively. Town Farm Bay Section (loose fragment).

Fig. 3.7.- Laminated dolostone bed illustrating a scour filled by algal mats. Initial laminae conform approximately to the scour shape. Later laminae are sub-horizontal and pinch out laterally on the initial laminae. Providence Island Section (6.25 m). Scale is in cm.

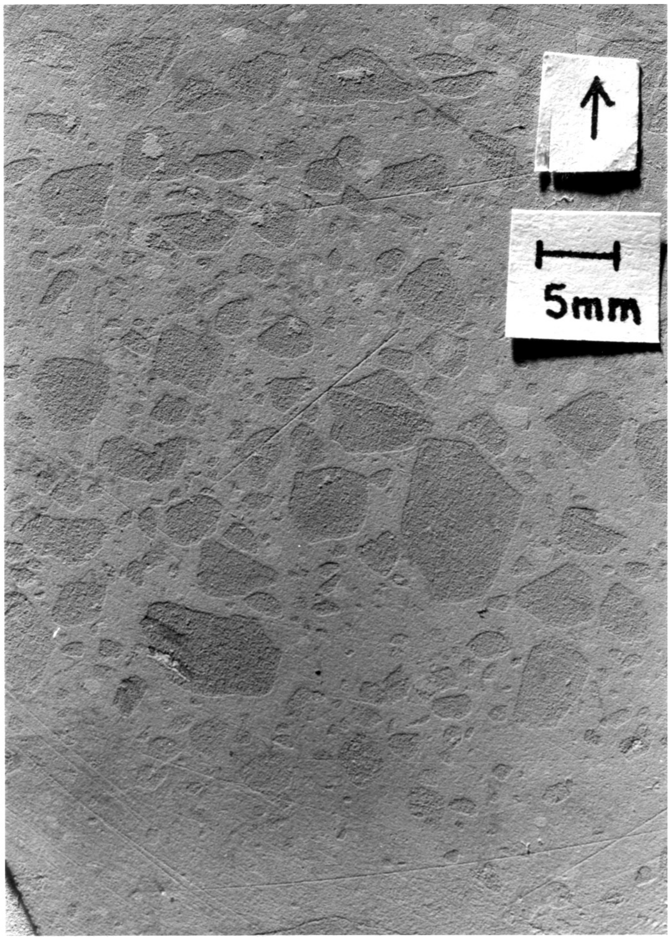

Fig. 3.8.- Polished and etched slab of calcareous dolostone showing an intraclastic scour-infill. Note different types of muddy lithoclasts; clasts with lower relief (after etching) are more calcareous. Also observe poor sorting and reverse/ normal grading at the bottom/top of the sample. Isle La Motte Section (3 m).

Fig. 3.9.- Dolostone bed illustrating a scour filled by lime mud with occasional intraclasts. Note truncation of the stromatolitic laminae. Providence Island Section (6.5 m).

and are almost absent in small channels. The compositional and textural considerations of the mud infill are almost the same as the above mentioned muddy intergranular matrix. A few lithoclastic intercalations may occur (Fig. 3.9).

Interpretation

Scours and small channels in tidal flats have been commonly regarded as local erosive features that have formed during tidal motions, storm surges, or generalized sheet flow (Reineck and Singh, 1973; Tucker, 1984). The relatively low abundance of these current structures within the formation possibly is related to the low energy regime of the depositional environment and, perhaps, to offlap or regressive accumulations within the tidal flat. These relationships occur in recent depositional environments in the Persian Gulf (Shinn, 1983).

Irregularly shaped scours with overhanging walls are thought to have been modified by burrowing organisms that tend to feed on previously scoured sediments. This interpretation is supported both by the presence of burrow fills identical to the scour fill and by burrow produced discontinuities within the underlying scoured sediments (Fig. 3.6).

The type of scour or channel fill seems to vary according to several factors. The main ones are probably current velocity, sediment availability and its movement over the bottom, water salinity, type and degree of lithification of the surrounding sediment, and scour or channel dimensions.

Infilling by algal mats occurs in scours or channels that may drain brine pools which formed at the supratidal zone (sabkha) probably by flooding during spring tides or storms and subsequent evaporation. These features are probably very similar to the prolific growths of recent algal mats in creeks that drain hypersaline tidal ponds (James, 1984).

Infillings by nearly equidimensional clasts probably result from scour or channel migration with subsequent erosion of the semi- or totally consolidated banks. The clasts may also reflect scour or channel erosion related to storm activity. Some flat-pebble conglomerates may have formed by the erosion and redeposition of mud polygons (Shinn, 1983). However, some flat intraclasts are clearly the product of the erosion of partially lithified or highly cohesive domal stromatolites by relatively turbulent water (2.4). The eroded flat algal fragments were easily carried by currents and concentrated in scours or small channels (Fig. 2.10A,B). This interpretation is consistent with the observation of similar processes in modern subtidal algal mat facies of Bermuda (Gebelain, 1969). It is uncertain if some of the flat intraclasts were derived from eroded planar stromatolites.

The term "flat-algal intraclast" seems to be appropiate. The term specifies and distinguishes these clasts from others with similar morphology but different origin. It seems likely that "flat-algal intraclasts" are common in other similar ancient tidal flat settings having domal and, perhaps, planar stromatolites. Intraclastic mudstone or wackestone infills may be the result of small-scale slumping activity, possibly from the sides of the channels. Initially, such slumps may have had a random distribution of clasts and matrix. With continued movement of the slump, the clasts appear to have become progressively concentrated toward the top of the deposit (Figs. 3.6 and 3.8).

Non-laminated muds probably are characteristic of scours that were infilled at very low current velocities and, perhaps, in settings with nearly normal salinities. The latter allows for the presence of algal feeders in the scour which burrow the sediment and prevent algal growth (as occur in homogeneous and mottled facies, 2.3).

3.4 Ripples and Cross-Bedding

Description

Ripples, as well as cross-bedding, have been observed only occasionally in the formation in relatively coarse-grained laminated dolostones or limestones and skeletal limestones (Fig. 2.2). Ripples occur within or, more commonly, on the upper surface of the beds. The observed ripples have symmetrical or slightly asymmetrical profiles and continuous straight crests. The ripple index (ratio of length to height; Reineck and Singh, 1980) generally ranges between seven and nine. Asymmetrical ripples found at Isle La Motte, Vermont (20 m; in Fig. 9.32) have crests running N 40^0 E with the steep lee slope facing south. At 37 m in the Boss Hogg's Quarry section, Vermont (9.2.4) (Fig. 9.21), cross-bedding shows a chevron or herringbone pattern of laminae (Fig. 3.10A). The individual laminae here frequently show discontinuities as well as small corrugations and irregularities in thickness (Fig. 3.10B).

Interpretation

The ripple index (seven to nine) unfortunately lies where the current and wave-forming fields overlap (Reineck and Singh, 1980). The asymmetrical ripples found in Isle La Motte, Vermont are probably current ripples since no bifurcation has been seen in their crests. Their trend, N 40^0 E, may approximate the orientation of the shoreline. The south-east facing lee side probably indicates the local offshore direction.

Herringbone cross-bedding is characteristic of tidal environments and is probably formed by flow and ebb tidal currents (Corrales and others, 1977). The irregularities in thickness found in some cross-beds of the Boss Hogg's Quarry section resemble those found in algal-produced laminations. Therefore, it is interpreted, for these particular cases, that algal mats covered the ripples. Such an interpretation

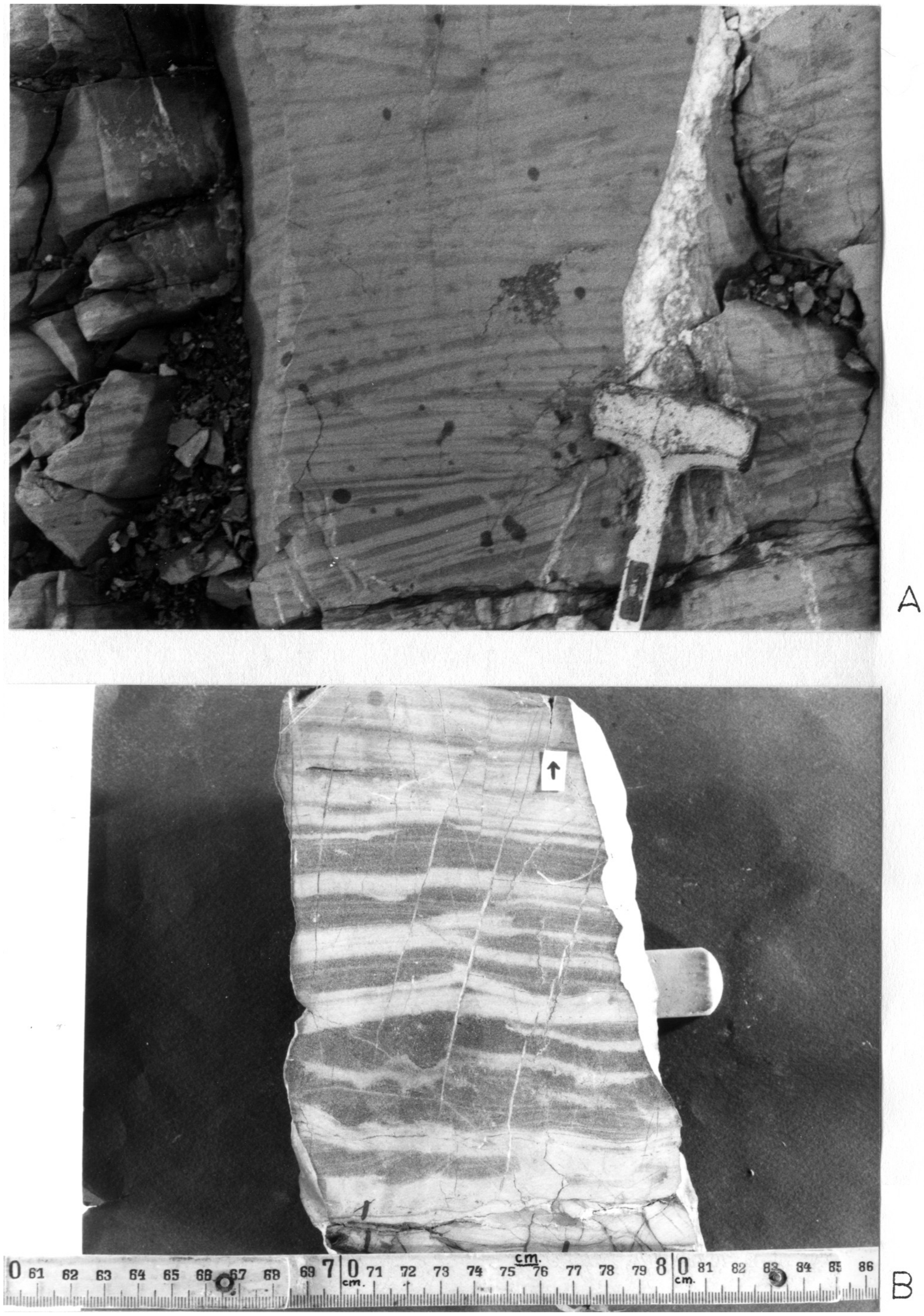

Fig. 3.10.- A) Dolomitic limestone bed showing ripple cross-lamination. B) Polished and etched slab from this bed. Note irregularities in thickness of the laminae which suggest that algal mats were covering ripples (see Fig. 3.11). Boss Hogg's Quarry Section (37.25 m).

Fig. 3.11.- Algal mats carpeting a ripple surface in 5 m of water. Whale Bay, Bermuda (Compare with Fig. 3.10).

is also supported by personal observations in Whale Bay, Bermuda, where recent subtidal algal mats cover a wave-formed rippled surface (Fig. 3.11).

3.5 Fenestral cavities or "birdseyes"

Description

These structures occur occasionally in dedolostones, laminated dolostones, and, to a lesser extent, in laminated limestones and mottled dolostones (Fig. 2.2). Both sub-spherical to irregular and planar cavities are filled with calcite spar. Sub-spherical to irregular fenestrae are mostly found in mottled sediments and in nearly homogeneous dedolostones. The cavities are 1 mm or less in diameter. They may be randomly distributed or concentrated in small particular areas (Fig. 3.12). Planar fenestrae almost always occur in association with algal produced laminations. They are parallel to the lamination and generally are less than 1 mm wide and less than 2 cm long (Fig. 3.12).

Interpretation

All fenestral cavities were probably formed by gas entrapment, desiccation, or air escape during flooding (Friedman and Sanders, 1978; Shinn, 1983). The gas formed by the decay of organic matter and, in the particular case of planar fenestrae, by the decay of algal tissue. Planar fenestrae may also form by wrinkles in algal mats produced by the above processes (Shinn, 1968b). Fenestral cavities

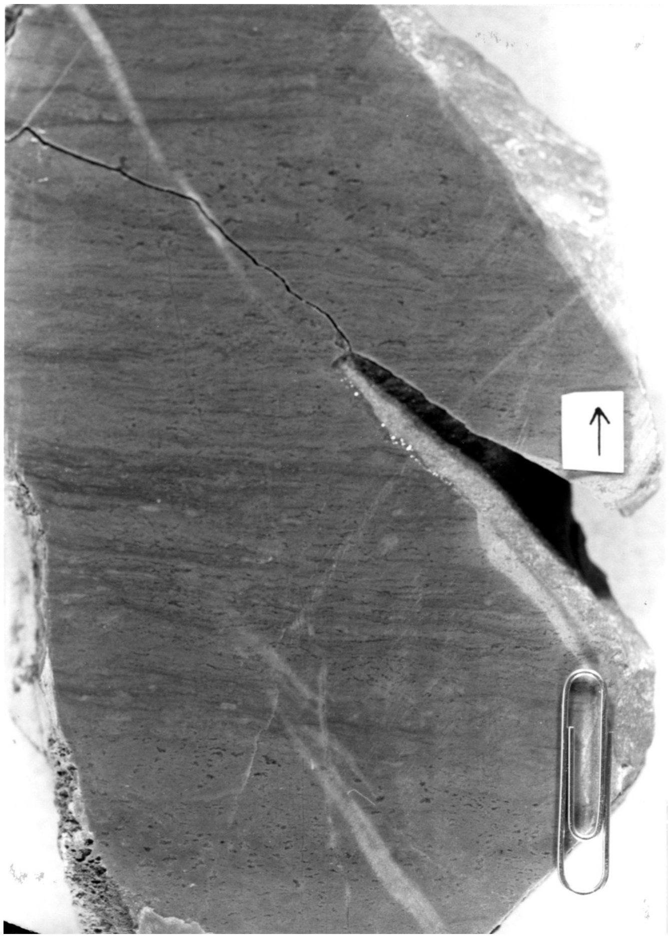

Fig. 3.12.- Polished and etched slab of laminated limestone showing sub-spherical to irregular (e.g. lower part) and planar (e.g. below center) fenestral cavities or "birdseyes". Note that planar fenestrae are parallel to bedding. Cavities are filled by calcite. Carver Falls Section (3.85 m). Arrow indicates top.

are preserved almost entirely in early lithified sediments from intertidal-supratidal environments (Shinn, 1983; Tucker, 1984).

4.- DIAGENETIC STRUCTURES

4.1 Carbonate and chert nodules

Description

Carbonate and chert nodules are distributed throughout the formation. They range from less than 1 mm to large structures 10 cm in average diameter. They are sub-spherical to irregular, or slightly flattened with the long axis oriented sub-parallel to bedding. The nodules, especially the carbonate types, frequently contain or are bordered by several elongated, prismatic, authigenic quartz or gypsum crystals as well as euhedral voids that usually range from 90 um to 180 um in size (Fig. 4.1). Authigenic quartz or gypsum may occur as intergranular or included phases. Nodules have sharp boundaries with the surrounding rock. They seem to occur mostly in association with dolomitic rocks and often are concentrated along particular beds. Their distribution is sporadic throughout the formation although they seem to be more frequent towards the base and top of the formation. In addition, nodules commonly occur in the non-laminated portions of laminated dolostones and, to a lesser extent, in mottled or homogeneous dolostones (Fig. 2.2). There are four main types of nodules:

a) Chert nodules: Chert nodules can be white or blue-black (flint) in color. Both varieties can coexist in variable proportions. Some beds may contain more white than blue-black varieties while others may show reverse proportions. Weathered nodules are somewhat scoriaceous in appearance. Chert nodules are composed of microquartz, megaquartz, and length-slow chalcedony (quartzine). Gradations from one particular form to the other exist. The size of microquartz and megaquartz crystals generally ranges from 2 um to 8 um and 50 um to 2.5 mm, respectively. Large megaquartz crystals often show undulous extinction. Chalcedony occurs as fibrous crystals, approximately 150 um long, that occasionally form radial aggregates 0.3 mm to 0.4 mm in diameter. Chert minerals in the flint varieties are slightly brownish in plane polarized light due to finely disseminated inclusions that are probably oxides. In addition, intergranular opaque phases, such as pyrite and Fe-oxides, frequently occur between the silica phases. Voids with angular corners to planar walls (possibly pseudomorphic voids after gypsum) are commonly filled by chert. Associated dedolomite crystals commonly truncate the chert phases (Fig. 4.2). Large, poikilitic, anhedral calcite crystals that occur in the nodules also produce similar truncations. However megaquartz crystals rarely penetrate or are molded by dedolomite rhombs. In this case, some of the intercrystalline boundaries are serrated. Nodular chert occurs more frequently within the lower 5 m of the formation and is only well exposed at Providence Island, Vermont (9.2.10) (Fig. 9.27).

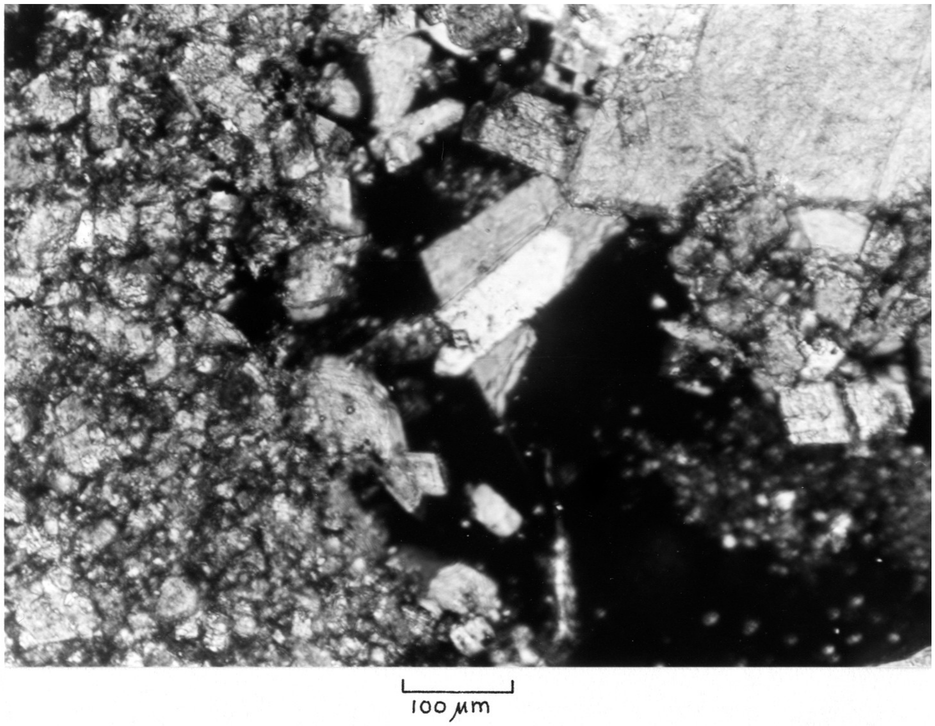

Fig. 4.1.- Photomicrograph illustrating gypsum crystal (clear; center) in calcite-dolomite nodule in mottled dolostone. Some phases (mostly calcite) have been lost during the making of the section. Saranac River Section (1.75 m).

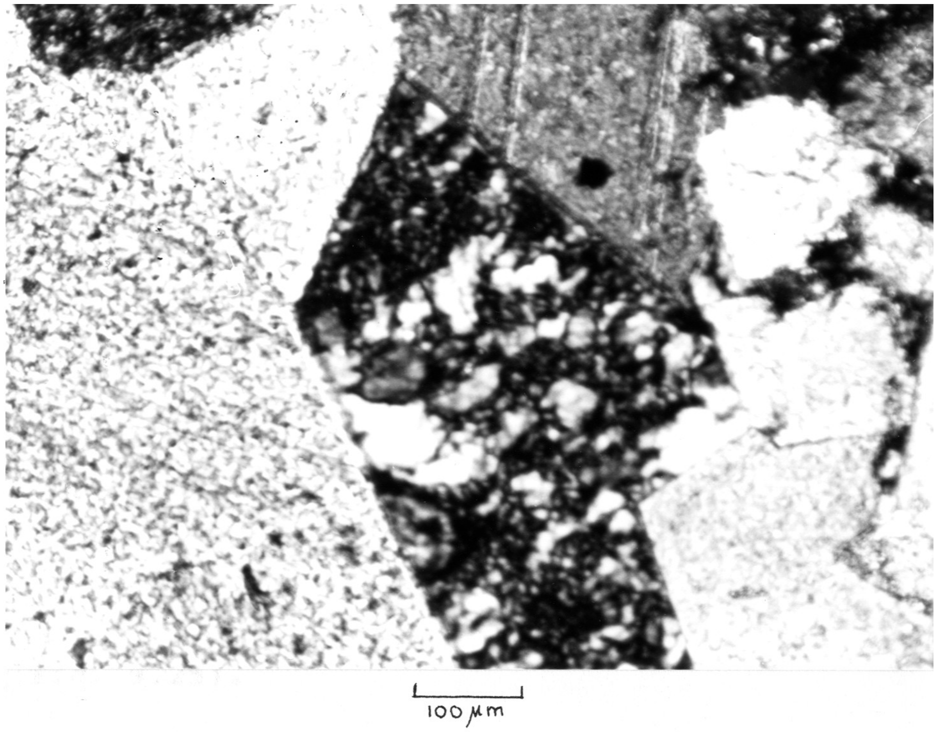

Fig. 4.2.- Photomicrograph showing chert (microquartz and megaquartz) pseudomorphing gypsum in dedolostone. Note that a dedolomite crystal (lower right hand corner) truncates the silica phases. The larger phases (top and left) are calcite crystals). Crossed nicols. Providence Island Section (6 m).

b) Calcite nodules: These are white or slightly pinkish in color. Calcite occurs as large, anhedral crystals up to 5 mm or more in size. These nodules seem to be more frequent at the base (white varieties) of the formation where they are associated with nodular chert or near the top of the formation where white and pinkish varieties are present (Member IV; 6.2).

c) Dolomite nodules: These are usually less than 1 cm in diameter. The dolomite crystals are up to 2.5 mm in size and are generally euhedral with curved cleavage planes or faces. These crystal forms represent saddle dolomite. The crystals are commonly slightly ferroan and show moderate pleochroism, from colorless to brown, due to micron-sized inclusions of probable matrix material that give a clouded appearance to the crystals. Although dolomite nodules are rare, they are more abundant near the top of the formation (Member IV, 6.2) where they are associated with calcite nodules (Fig. 9.25).

d) Calcite-chert nodules: These nodules are generally slightly smaller than chert, calcite, or calcite-dolomite nodules (below). The chert is commonly white and consists mainly of megaquartz crystals which line the perimeter of the nodules. The large anhedral calcite crystals are restricted to the core of these nodules. As in the case of chert nodules these nodules are more frequently found at the base of the formation (Fig. 9.27).

e) Calcite-dolomite nodules: Dolomite generally occurs as saddle dolomite that lines the outer margins of the nodules and which is identical to that in dolomite nodules (described above). Calcite, which is restricted to the core of the nodule, is similar to the pinkish varieties found in calcite nodules (above) (Figs. 2.4B and 4.3). Euhedral gypsum and, to a lesser extent, anhydrite crystals are occasionally present. These evaporite phases are more common in these nodules than in the other types. Gypsum and authigenic quartz crystals are commonly associated and are comparable in morphology and size. Both phases also contain micron-size inclusions of unknown material. However, gypsum is easily distinguished by its negative relief (Fig. 4.1). Chert is found as an accessory phase in these nodules. Voids with the euhedral outline of gypsum crystals are commonly present. It is believed that these voids represent gypsum crystals that have been dissolved during the process of making thin-sections. The voids commonly are penetrated by dolomite rhombs and often show corroded margins. Chert also commonly molds or is penetrated by dolomite. These nodules are only frequent in the uppermost part of the formation where they are associated with pinkish calcite and dolomite nodules (Fig. 9.25).

Interpretation

Most, if not all, carbonate and chert nodules are interpreted as replacements of primary anhydrite and/or

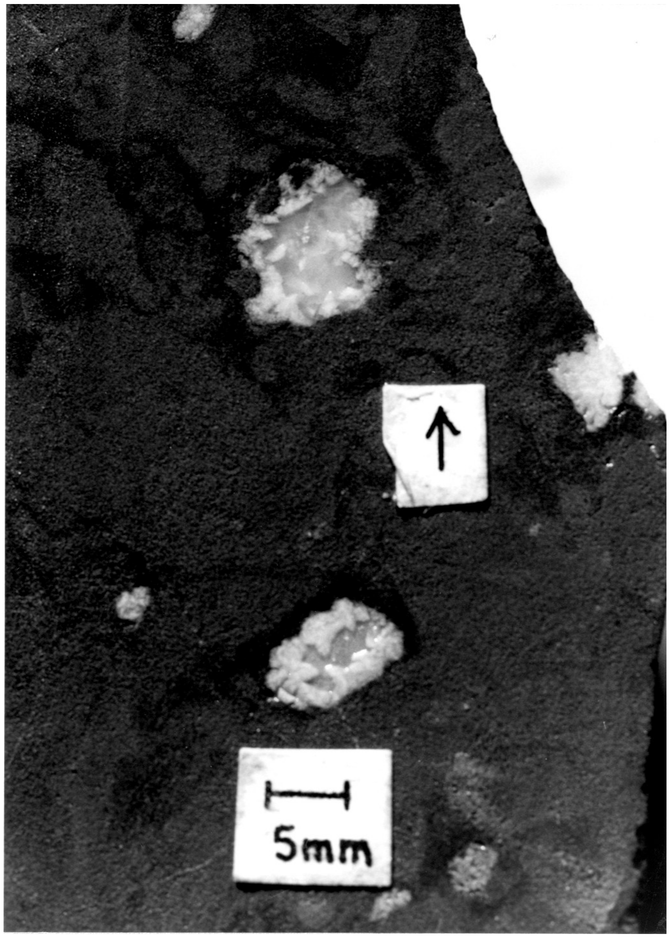

Fig. 4.3.- Polished and etched slab of mottled dolostone illustrating calcite-dolomite nodules. Note that dolomite (with higher relief after etching) lines the perimeter of the nodules whereas calcite is restricted to the cores. Saranac River Section (1.75 m). Arrow indicates top.

gypsum nodules. This interpretation is based on several lines of evidence. The most important of these is the presence of gypsum and anhydrite crystals which represent the earlier phases of the nodules on the basis of crystal boundary relationships. In addition, the existence of unfilled euhedral voids suggests the presence of relict evaporites that have been dissolved during the process of making thin sections. Authigenic quartz and, to a lesser extent, chert frequently retain gypsum crystal shapes (Fig. 4.2). The presence of length-slow chalcedony also indicates the former presence of evaporites (Folk and Pittman, 1971). The nodules are similar in shape and size to recent anhydrite nodules. However, anhydrite nodules may be pseudomorphs of the gypsum crystal mushes which commonly grow within recent intertidal sediments (Kendall, 1984). It seems possible that similar gypsum growths are the precursor of many nodules of the Providence Island Formation because gypsum pseudomorphs commonly appear in lower intertidal mottled and upper intertidal algal laminated deposits.

The presence of relatively large gypsum or anhydrite crystals within some of the nodules is very significant because they apparently have not been reported in similar nodules distributed through the Beekmantown Group. However, nodules and individual pseudomorphs after evaporites have been widely reported (e.g. Tribes Hill Formation; Curl and others, 1984). The diagenetic processes involving the precipitation and subsequent replacement of evaporites will be discussed in chapter 5. The color shown by the nodules is probably due to finely disseminated mineral impurities within or between the major mineral phases.

4.2 Bedded chert and chert lenses:

Description

These are blue-black colored and only a few centimeters thick. The beds are commonly irregular, wavy, and discontinuous. The lenses are usually less than 1 m in lateral extent and are similar and frequently associated with chert beds (Fig. 4.4). These beds occasionally show diapiric structures in which individual diapirs may or may not be connected to the bed (Fig. 4.4). Their occurrence within the formation, the type of host rock and their mineralogical and textural considerations are essentially identical to the blue-black chert nodules. However, bedded varieties are more uncommon than nodular ones.

Interpretation

These beds are interpretated as pseudomorphs of pre-existing anhydrite or gypsum beds on the basis of the same lines of evidence as those proposed for the blue-black chert nodules. In addition, the occurrence of diapiric structures may also reflect the former presence of evaporites. These beds could have been deposited in the supratidal zone (sabkha) from a highly concentrated brine that formed by marine flooding of the sabkha and subsequent evaporation

Fig. 4.4.- Bedded chert and chert lenses in partially laminated dolostone bed. Note the presence of diapiric structures suggesting that chert is pseudomorphing evaporite beds or lenses. Providence Island Section (20.75 m).

(5.2). A modern example could be the bedded gypsum that accumulates in pools marginal to the Red Sea (Friedman and Sanders, 1978). Another possible interpretation is that these beds may have replaced layers of gypsum mush or, perhaps, anhydrite that commonly form in modern carbonate settings in the transitional zone between the intertidal and supratidal zones (Kendall and Skipwith, 1969). The discontinuous character of many of the beds could in part be related to the removal of evaporitic material as a consequence of diapirism.

4.3 Solution-collapse breccias

Description

These consist of angular clasts of several lithofacies that range in average diameter from 1 mm or less to 5 cm or more. The matrix frequently consists of dedolomite crystals usually ranging from 70 um to 200 um in size (Figs. 2.4A, 4.5 and 4.6). Terrigenous material, particularly quartz, may constitute up to 20% of the matrix and appears as disseminated grains ranging between 40 um and 80 um in size. Small voids, up to 1 mm in size, are filled with chert. These occasionally have outlines that are identical to gypsum crystals found in calcite-dolomite nodules (4.1).

Carbonate and chert nodules are structures that are commonly associated with the breccias. The larger nodules are commonly associated with larger breccia fragments. The

Fig. 4.5.- Polished and etched slab of dolostone showing solution-collapse breccia. The matrix contains dedolomite. Providence Island Section (loose fragment). Arrow indicates "top" of the fragment as it was found.

clast-matrix boundary is frequently stylolitic.

Interpretation

These breccias are probably the result of the collapse and brecciation of overlying deposits due to the dissolution of pre-existing evaporites.

4.4 Stylolites

Description

They are sub-horizontal and, more rarely, inclined or sub-vertical. Stylolites are sutured or wavy seams that consist of variable concentrations of micron-size pyrite crystals, carbonaceous material, Fe-oxides, and clays (?). Clastic material, as well as dolomite rhombs, may be present but usually in insignificant amounts. The relative proportions of the components depend on the general composition of the rock in which the stylolites are located. Pyrite and carbonaceous material commonly appear in similar proportions, which usually exceed 20% of the material of the seam. Structures or particles adjacent to stylolites are truncated or partially missing. Sutured seams are always located within beds, and they frequently define the margins of channel fill intraclasts or solution-collapse breccias when the clasts have a strong compositional and textural contrast with the surrounding matrix (Fig. 2.4A). Wavy, irregular seams appear within or, more commonly, separate bedding planes and are frequently characterized by warty surfaces that resemble an "egg carton." Wavy stylolites occasionally appear as laminations or form thin beds up to 2-3 cm thick that are parallel to bedding. In the latter case, they could be mistakenly interpretated as sedimentary shaly partings if they are not observed in great detail. Stylolites appear to be more common in thin, very fine grained carbonate beds.

Interpretation

Stylolites have been commonly regarded as the insoluble residue remaining from the dissolution of carbonates by pressure-solution. This process is related to overburden or tectonic pressure. The dolomite rhombs occurring in some stylolites are not an insoluble residue and therefore, are probably late in origin (Zenger, 1972). For more details about the development of stylolites, see chapter 5.6.

4.5 Joints and veins

Description

These structures generally are sub-vertical, 3 mm or less in width, and rarely exceed 1 cm. Most of the joints are filled by veins of white chert or carbonate minerals. In the latter case, euhedral dolomite crystals line the joint surfaces and anhedral calcite crystals occupy the remaining internal space. Dolomite crystals are up to 0.15 mm in size and, generally, are zoned so that a cloudy, pleochroic, commonly ferroan core is surrounded by a clear ferroan rim.

This zonation is similar to that shown by the dolomite crystals that fill voids. However, this distribution of Fe^{2+} is in sharp contrast with many of the dolomite rhombs of the host rock where similar cores are surrounded by clear, non-ankeritic rims. Some joints or small-scale faults are frequently associated with solution-collapse breccias (Fig. 4.6).

Interpretation

The diagenetic origin of some of the joints is inferred by their truncation by stylolites and by their close association with solution-collapse breccias (Fig. 4.6). Other joints are clearly late diagenetic or post-diagenetic in origin since they cut through the other existing structures, including stylolites. These joints are thought to be dilational since no evidences of replacement of host material by the vein material has been seen. The relative timing of those veins that are not associated with any of the other diagenetic structures is uncertain.

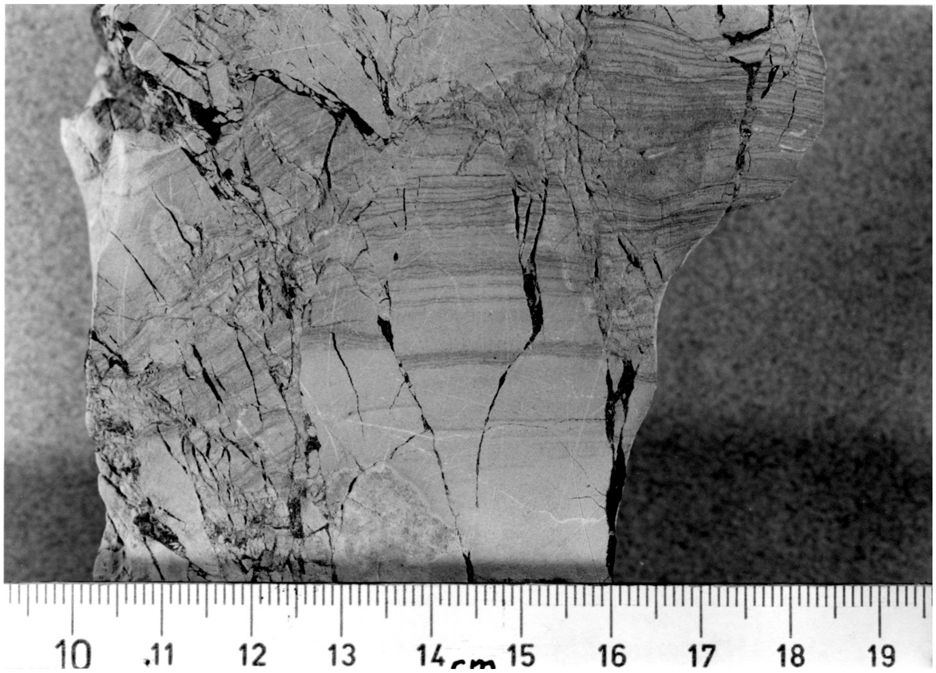

Fig. 4.6.- Polished and etched slab of laminated dolostone showing diagenetic joints associated with solution-collapse breccias. The joints are filled by veins of chert and carbonate (calcite and/or dolomite). Providence Island Section (20.5 m).

5.- DIAGENESIS

Several diagenetic processes have modified the deposits of the Providence Island Formation although they do not equally affect each of the occurring lithofacies. A six-step sequence is proposed for the various stages of diagenesis. This sequence is inferred by examining the characteristics of the texture, structures, and mineral or particle constituents of the rocks.

5.1 Synsedimentary cementation or cohesiveness ?

It appears that most of the original lime mud, whether or not laminated, has been partially or totally cemented by calcite or aragonite or was highly cohesive. This hypothesis is based on the presence of burrows that apparently lack wall linings (Fig. 2.1), scours with overhanging flanks (Fig. 3.6), and muddy lithoclasts from the eroded flanks of scours or small channels (Figs. 3.8 and 2.14). The disruption of algal domes into flat algal lithoclasts by water turbulence (2.4) may either reflect an algal induced cementation of stromatolitic rocks or suggest that the clasts were unlithified but cohesive. Modern examples of synsedimentary cementation and cohesive carbonate sediments include early aragonitic cementation of the algal flats of the Persian Gulf (Kendall and Skipwith, 1969) and the unlithified, but cohesive algal "flat chips" that occur in the subtidal environments of Bermuda (Gebelain, 1969), respectively.

5.2 Precipitation of evaporites, dolomitization, and pyritization. Sabkha diagenesis

Dolomitization represents the most prominent diagenetic alteration that affects most of the deposits of the Providence Island Formation. As has already been stated, dolomite probably has formed by the replacement of a calcareous mud (2.3). Its diagenetic origin is also inferred by the fact that dolomite commonly conforms to, includes, or penetrates terrigenous material.

There are some reasons to believe that the dolomitization appears to be related to sabkha diagenesis. Recent sabkhas are highly active diagenetic environments (Kendall, 1984) and their presence in the depositional setting of the Providence Island Formation has been inferred in chapters 2.3, 3.3, and 4.2. In addition, the fine-grained size of the dolomite crystals, the preservation of diagnostic tidal flat sedimentary structures, as well as the close association of dolomite-gypsum/anhydrite (or their pseudomorphs, 4.1 and 4.2) indicates selective dolomitization within a very short time after the deposition of the sediment. These features are characteristic of sabkha diagenesis (Shearman, 1963; Tucker, 1984).

The exact mechanisms inducing dolomitization are difficult to infer. Based on field observations and, also, on data documented from modern sabkhas (Patterson and Kinsman, 1982) it is thought that "flooding-reflux" appears to be the most important mechanism contributing to the dolomitization of many of the deposits of the Providence Island Formation. It has been previously suggested that brine pools formed at the sabkha by probable flooding during spring tides or storm surges and subsequent evaporation (3.3). It is also believed that the brine pools not only drain to the ocean through scours or small channels but also by percolation through the underlying sediments. The existence and the reflux of brine fluid in the depositional environment of the Providence Island is supported by the presence of: a) evaporites or their pseudomorphs as diagenetic features within the sediments, b) structures suggestive of downward dolomitization, and c) characteristics of the rock fabric, such as the presence of overgrowths in dolomite, and several generations of pyrite.

The occurrence of nodular or bedded chert and carbonate nodules, which are pseudomorphs after evaporites, appear to be restricted mostly to dolomitic lithofacies (4.1 and 4.2). Their evaporitic precursors probably precipitated in the framework of sediment particles of the sabkha or underlying lithofacies when the salinity values of the inferred original brine are within the field of $CaSO_4$ precipitation due to intense evaporation (Friedman and Sanders, 1978). Since evaporites or their pseudomorphs occur mostly in the form of isolated crystals or nodules, respectively (4.1) and not as complex masses with a characteristic chickenwire texture or as layers contorted into enterolithic shapes, it seems possible that there are fluctuations within the field of $CaSO_4$ precipitation due to variable dilution of sea water by meteoric water from adjacent emergent reliefs or from percolation of brackish water collected in the supratidal area or both (James, 1984). Also, the presence of brackish groundwater probably indicates more frequent semiarid rather than arid conditions for the original depositional environment (7.1). Another alternative from fluctuations within the field of CaSO4 precipitation is that the salinities of brines formed on the sabkha are not very high. The precipitation of CaSO4 raises the Mg/Ca ratio of the percolating brine which then causes downward dolomitization of the original lime mud in contact with this fluid (Patterson and Kinsman, 1982). The dolomitization of calcareous sediments in contact with brines with high $Mg{+}{+}/Ca^{++}$ ratios is a commonly invoked process (Zenger, 1972; Kendall, 1984). Another factor controlling the dolomitization of the original carbonate mud could be the presence of anaerobic bacteria in the brine fluid (Sonnenfeld, 1984). Most sulfate ions in inflowing sea water are tied to magnesium ions and are not dissociated in the brine. The sulfate removal due to the metabolism of anaerobic bacteria leads to a deficiency of sulfate anions and produces an excess of magnesium cations which are available for dolomitization. The dolomitization of lime mud is accompanied by a notable increase of the grain size of the rock.

The frequent restriction of detrital quartz or pyrite inclusions to the outer rims of the dolomite crystals (2.3) may suggest that the internal cloudy cores may represent the initial replacement of precursor carbonate particles or that some of the cores were originally wind blown detrital dolomite crystals (2.11), or both. Downward dolomitization is supported by the occasional presence of limestone beds that are increasingly dolomitized toward their top (Fig. 5.1). This interpretation is consistent with observations at San Andres Island, Colombia, where downward percolating brines with a high Mg/Ca ratio that formed in the supratidal spray zone cause the dolomitization of cliff-forming Pleistocene limestones (Tucker, 1984), and with observations at the Trucial Coast of the Persian Gulf where dolomitization takes place only in the storm recharge zone (Patterson and Kinsman, 1982).

VanTuyl (1916) has suggested that the dolomitization of fine-grained limestones begins at certain centers and spreads out from these. Unfortunately, no evidence has been found in the formation to support such an interpretation. Dolomitization not only involves an interchange of Mg++ and Ca++ ions but probably also affects other components such as trace elements and their isotopes, carbon and oxygen isotopes, and is influenced by CO_2 activity, pH, and temperature (Land, 1983).

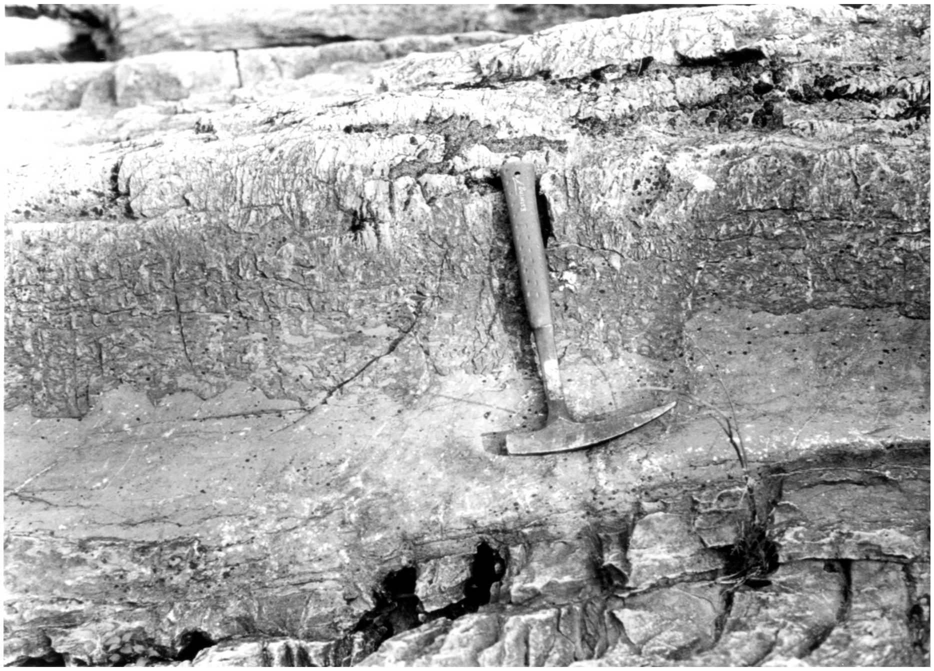

Fig. 5.1.- Limestone bed which progressively becomes a dolostone towards its top. This feature could be evidence of downward dolomitization. Carver Falls Section (21m).

Other possible factors contributing to the dolomitization of the deposits of the Providence Island Formation could have been: 1) synsedimentary cementation, 2) evaporative pumping (Hsu and Siegenthaler, 1969), 3) capillary concentration (Shinn, 1983), 4) seepage-reflux (Adams and Rhodes, 1960), 5) changes of pH associated with respiration and photosynthesis of blue-green algae (Shinn, 1983), and 6) mixing of marine and continental groundwaters (Folk and Land, 1975). Synsedimentary cementation probably by aragonite or calcite (5.1) may have contributed to the raising of the Mg/Ca ratio of the porewater and hence, to dolomitization. Changes of pH induced by algae may explain the frequent occurrence of dolomitic laminae in fine grained limestone beds. Such laminae probably represent algal mats which are interbedded with lime mud (2.7). The presence of these algal mats also enhances selective dolomitization since blue-green algae concentrate magnesium in their cell material during growth and, as they decompose, Mg-rich organic compounds are released (Owen and Friedman, 1984). A mixing of marine and continental groundwaters may have been possible since the presence of underground brackish water has previously been inferred by analogy with modern settings (above). However, the contribution of this mechanism, if contributed, is believed to be small given the semiaridity or aridity of the environment

The conditions favoring an alternation of limestones and dolostones are unknown. Shinn (1983) has documented resistant crusts in modern carbonate settings that result from the cementation of winnowed grainstone layers that may retard the vertical movement of fluids. However, the calcareous units or beds of the Providence Island Formation frequently do not contain grainstone horizons at their base or top that, if cemented might retard or prevent the vertical movement of dolomitizing fluids. The presence of shale seams or beds within the deposits of the formation apparently did not prevent the dolomitization of calcareous deposits either above or below the shales (Figs. 9.20 and 9.32).

Pyritization seems to have occurred simultaneously with dolomitization because pyrite crystals may appear as inclusions in the dolomite overgrowths (usually with coarser grain size towards the dolomite outer rim) or as penecontemporaneous intergranular phases between the dolomite rhombs (2.3). The overgrowths shown by the larger dolomite crystals as well as the presence of what appears several generations of pyrite suggest that both dolomitization and pyritization took place during several and succesive stages. These stages are thought to be related to such external environmental factors as sporadic floodings of the supratidal sabkha during spring tides or storms. Relatively large pyrite crystals occur mostly associated with coarse grained dolomitic deposits (e.g. CPA laminae) which commonly contain higher concentrations of terrigenous and allochemical material and a lower content of intergranular matrix as compared to finer grained deposits (e.g. FM laminae). It is thought that these coarse grained dolomitic deposits reflect sediments whose original permeabilities were relatively high. This relationship has also been noted by Shinn (1983) in recent carbonate sediments. In view of the fact that pyrite is more abundant in coarser-grained and matrix-poorer deposits (e.g. CPA laminae; 2.4) it is thought that matrix has contributed to the formation of pyrite crystals in relatively permeable sediments. The matrix contains significant amounts of carbonaceous material which derives from organic matter. Therefore, it is believed that pyrite probably results from the bacterial decomposition of organic matter in SO_{42-}-bearing interstitial water following the reaction (Friedman and Sanders, 1978):

$$CaSO_4 == Ca2+ + SO_{42-} \quad (1) \qquad \text{and then}$$

$$SO_{42-} + 2CH_{2}O \text{ (organic matter) } == H2S + 2HCO3= \qquad (2)$$

The H_2S reacts with the Fe2+ in solution to produce pyrite (Berner, 1970). The Fe^{2+} in the porewater probably is liberated mostly from clays and ferric oxides in the sediment by the negative Eh (Tucker, 1984), a feature that has previously been inferred (3.1). As a result of this, an increase of the bacterial decomposition of organic matter leads to an increase of the pyrite content of the deposit. The primary precipitates probably are metastable iron sulfides, such as machinawite and greigite which, in a short time, are transformed to pyrite (Tucker, 1984). The partial reabsorption shown by many terrigenous quartz grains probably reflects a high pH during dolomitization and pyritization (Shukla and Friedman, 1983).

5.3 Precipitation of calcite

Anhedral calcite crystals frequently occur in the relatively coarse-grained deposits of the Providence Island Formation as the latest intergranular phases. The precipitation of calcite probably results from the following reaction which follows reactions 1 and 2 (5.2) (Friedman and Sanders, 1978):

$$Ca^{2+} + 2HCO_3 == CaCO3 + H2O + CO2 \quad (3)$$

It is thought that during the beginning of dolomitization and pyritization that Ca2+ released during reaction 1 (5.2) was probably removed by the passage of the brine through the relatively permeable sediment. The removal of by-products of diagenetic reactions and non-accumulating ions by fluids beneath the sabkha surface has been documented by Kendall (1976). At this early stage, calcite is probably not stable due to the high Mg/Ca ratio of the interstitial fluid, and clean dolomite crystals grow at the expense of the more soluble calcite (Bathurst, 1975). The dolomite overgrowths as well as several generations of pyrite that result from succesive dolomitization and pyritization events, probably lead to the reduction of the porosity. As a result, the Ca^{2+} released in reaction 2 (5.2) can not easily be removed from the pore space. Thus, a decrease of the porosity or permeability values of the deposit probably influences the precipitation of late interstitial calcite. Also, this late calcite could simply reflect a change in the pH of the diagenetic environment. The latest dolomite overgrowths probably are as soluble as the calcareous surface, and, therefore, the two minerals can coexist in a pseudoequilibrium. At this stage, further dolomite can not grow because its overgrowth would be more soluble than calcite (Weyl, 1967; Bathurst, 1975).

5.4 Dissolution of evaporites and void/joint infill by chert and carbonates

The presence of anhydrite and/or gypsum pseudomorphs in chert or carbonate (4.1) as well as of dedolostones and solution-collapse breccias probably reflects the dissolution of evaporites by meteoric waters. Based on the chert-dedolomite crystal boundary relationships (4.1), it appears that the diagenetic emplacement of chert is prior to dedolomitization (Fig. 4.2). Chert appears to fill the undestroyed voids or breccia pores (MO and BR types, respectively, of Choquette and Pray, 1970) after the collapse of the sediment due to the dissolution of evaporites.

The source of the silica is problematical. Silica may have been added to the water by volcanic emanations or may have been freed by the alteration of volcanic ash. The presence of volcanic ash has been inferred by the presence of authigenic K-feldspar in other Early as well as Middle Ordovician deposits which are located approximately in the same geographic area as the Providence Island Formation (Buyce and Friedman, 1975; Dolfi and Friedman, 1983). However, preserved volcanic ashes have not been documented in the Taconic Allochthon rocks that were deposited before the Black River Group (Late Ordovician). As a result, the K-feldspar crystals or overgrowths on detrital grains that are occasionally observed in the carbonate lithofacies of the Providence Island Formation may represent late diagenetic phases or features that formed at low temperatures by the reaction of connate brines with intercalated siliciclastic debris (Hearn and Sutter, 1985). Silica may also derive from the mineral transformation of montmorillonite to illite during diagenesis (Hawkins, 1978). Nevertheless, chert-rich and chert-free deposits appear to contain small and similar amounts of clays within the matrix. As a result, there is some reason to believe that silica resulting from the alteration of detrital quartz and/or from the dissolution of radiolaria, and/or sponge spicules (Tucker, 1984) appear to be the most likely sources of silica. The exact mechanisms for the precipitation of silica also remains uncertain. A possible interpretation is that as the silica-rich solution becomes enriched in sulphate as a consequence of the dissolution of evaporites, silica is forced to precipitate as microquartz, megaquartz, and length-slow chalcedony (Folk and Pittman, 1971).

Voids left by the dissolution of evaporites may also be filled by saddle dolomite and/or calcite (4.1). Crystal boundary relationships indicate that the precipitation of calcite postdates that of chert or dolomite (4.1). Since chert phases are occasionally penetrated by saddle dolomite crystals it appears that saddle dolomite crystallized after chert. The relative timing between the precipitation of saddle dolomite and dedolomitization as well as compaction (below) is uncertain.

Saddle dolomite crystals are curved probably by variations in concentration of Ca^{2+} along growth laminae (Radke and Mathis, 1980). The precipitation of these late dolomite crystals may result from the dilution of saline pore-water with meteoric groundwater (Folk and Land, 1975) in deposits where evaporites are not abundant. The later precipitation of calcite may occur in the very shallow subsurface through evaporation of vadose or near-surface phreatic groundwater (Tucker, 1984). It is tentatively proposed that the timing and chronological order for the precipitation of chert, ferroan dolomite, and calcite in diagenetic joints (4.5) is the same as for the above mentioned voids or breccia pores. This interpretation is based on the textural and compositional features of the infilling phases as well as on the frequent association of these structures.

5.5 Dedolomitization

Dedolomitization is a process that is characterized by the conversion of dolomite to calcite (2.9). This process appear to have occurred in association with the dissolution of gypsum/anhydrite crystals, nodules or beds. Several lines of evidence support this interpretation. The presence of solution-collapse breccias (Fig. 2.4A), chert and carbonate nodules that are pseudomorphs after evaporites (Fig. 9.27), and, to a lesser extent, gypsum and anhydrite crystals in the dedolostones reflects the former presence of evaporites which have been mostly dissoved or replaced. The dissolution of gypsum or anhydrite by meteoric water probably leads to a significant decrease of the Mg/Ca ratio of the pore water which induces the dedolomitization of the dolomite crystals in contact with this fluid (Evamy, 1967).

5.6 Compaction and stylolitization

Compaction and stylolitization are diagenetic physical processes that have been frequently attributed to depth of burial and/or tectonic pressure. Compaction involves dewatering and a closer packing of the constituent particles (Tucker, 1984). Differential compaction features are common in laminated deposits that contain burrows which have a sharp compositional and textural contrast with the surrounding material (3.1) (Fig. 2.4D). Certain burrows are believed to be originally vertical and straight and therefore, they could be considered as compaction markers.

Thus, the approximate degree of compaction of certain deposits, such as burrowed FM-CPA alternating laminae (2.4) (Fig. 2.4D) has been estimated. The burrows of these deposits have been compacted approximately to 30% of original thickness, the FM type laminae to 70%, and the CPA type laminae from 10% to 30%, approximately. Because 65% to 75% of the rocks of the Providence Island Formation have a grain size similar to FM type laminae it is thought that this formation as a whole has compacted by 50% or, perhaps, more.

Originally, FM and CPA type laminae consisted of lime mud although the latter contained higher amounts of terrigenous and allochemical material (2.4). The relative timing of compaction with respect to the other diagenetic processes is problematical. One possibility is that compaction occurred prior to dolomitization. In this case, deposits with higher amounts in terrigenous and allochemical constituents and, hence, with higher original permeability values (e.g. CPA type laminae) were more cemented and subsequently less compacted than sediments containing lower amounts of these constituents (e.g. FM type laminae). Possible evidences for synsedimentary cementation have been discussed in chapter 5.1. Another alternative is that compaction postdates dolomitization because the grain size of dolomitic rocks is mostly a diagenetic feature (5.2) and the degree of compaction varies for deposits with different grain size such as FM and CPA type laminae (above). There are no evidences for the relative timing between the compaction and the diagenetic processes that occurred after dolomitization.

Stylolites are believed to represent late diagenetic or post-diagenetic structures since they cut through most of the other associated diagenetic features. Unfortunately, the cross-cutting relationships between stylolites and late diagenetic or post-diagenetic joints have not been observed.

Stylolites are pressure-solution features that probably develop preferentially at boundaries between beds or horizons having a high compositional and/or textural contrast. This interpretation is supported by the observation of stylolitic seams in channel-fill lithoclasts or solution-collapse breccias. Clasts having a strong compositional and textural contrast with the surrounding matrix are the only ones that show frequent stylolitic margins (4.4) (Fig. 2.4A). As a result of this, the position of wavy stylolites parallel to bedding is probably controlled by shale seams in carbonate. Hence, the composition of wavy stylolites is due to the constituent minerals of the shale seam and on the insoluble residue resulting from the dissolution of carbonates above and below the shale seam. The common presence of stylolites through the formation poses the problem of estimating the amount of dissolved carbonate. It is evident that the original carbonate content in the formation was higher than now.

The implications of stylolite formation at depth and the upward expulsion of brine fluid due to compaction as a contributing factor in shallower diagenetic processes, such as precipitation of silica or calcite are uncertain. Unfortunately, due to the scarcity of terrigenous minerals in the carbonates, truncation of quartz or feldspar grains by stylolites has not been observed.

6.- STRATIGRAPHY

6.1 Chronostratigraphy

Fisher (1977) has interpreted the Providence Island Formation as a unit varying in age from early-middle Cassinian in the southern Lake Champlain lowlands to late Cassinian in the northern Lake Champlain lowlands. Fortey (1980) based on observations on trilobite faunas such as *Bathyurina* has suggested that the top of the Providence Island Formation in western Vermont is late Cassinian in age. However, Landing and others (submitted) have noted middle Whiterockian conodonts (e.g. *Paraprioniodius costatus*) in thin-bedded limestones of the upper portion of the Providence Island Formation on Isle La Motte, Vermont. Since no index fossils have been found in the formation during this study a Late Canadian and middle Whiterockian age is assumed in this study.

6.2 General statement

The Providence Island Formation forms the top of the Beekmantown Group. This formation does not show major lithological changes in the area of study. The base of the formation is represented in two sections: the Providence Island (Vermont) and the Deweys Bridge Road (Comstock, New York) sections (Fig. 1.1). At these outcrops a contact between the Providence Island and the Fort Cassin Formations can be observed (Figs. 9.17 and 9.27). The highly fossiliferous, probably subtidal, wackestone to packstone beds of the top of the Fort Cassin Formation give way abruptly to the fine-grained almost unfossiliferous, intertidal dolomitic lithofacies of the Providence Island Formation. The section at Providence Island (9.2.10) is the only continuous exposure of the base of the formation. At this outcrop a total of 21 m of rock has been recorded. The base of the formation at this locality can be easily recognized by its abundant laminated dolostones, white and blue-black chert nodules, carbonate nodules, and intercalations of dedolomite beds or horizons. The rock color varies from medium gray at the base of the Providence Island section to medium dark gray at its top (Fig. 9.27). The Deweys Bridge Road section is very discontinuous and only the lowest bed, 1.5 m. thick, has been recorded (Fig. 9.17). This bed appears to correlate lithologically with the lowest bed of the Providence Island section. Although the latter appear to contain more calcite-chert nodules as well as some dedolomite horizons, these characteristics probably are not very critical for correlation since nodules or dedolomites are post-depositional diagenetic features (4.1 and 2.9). The discontinuous outcrops of the Providence Island Formation in immediate proximity of the Deweys Bridge Road section show lithofacies that resemble those of the Providence Island section. Therefore, it seems likely that the basal deposits of the Providence Island Formation at the localities of Providence Island and Deweys Bridge Road are lithologically correlative without major lateral or vertical changes in facies and lithology.

The upper contact of the formation crops out in four localities. From south to north they are: Carver Falls (Vermont), Town Farm Bay (Vermont), South Hero (Vermont), and Isle La Motte (Vermont) (Figs. 6.1, 9.20, 9.25, 9.28, and 9.32). This contact is characterized by the presence of an unconformity which separates the Providence Island Formation from the overlying Chazy Group (6.5). The upper lithofacies of the Providence Island Formation at the sections of Isle La Motte, Shoreham, and Town Farm Bay are very similar and hence are believed to be lithologically correlatives. Based on the observation of these sections four members have been recognized in the upper part of the formation. The lowest one (Member I) is about 2-3 m thick and is made up of limestones. It is observed at the Town Farm Bay section approximately between 57 m and 59 m (Fig. 9.25). The limestones are here skeletal and, to a lesser extent, mottled and laminated. The mixed, mostly laminated, dolomitic-calcareous deposits of the Isle La Motte section (0.5 m - 3.3 m; in Fig. 9.32) probably represent Member I since these deposits at both the Isle La Motte and Town Farm Bay sections are approximately at the same distance below the base of Member III (below) (Fig. 6.1). Member II is approximately 15 m thick and represents a dolostone dominated sequence. The overlying Member III is composed of limestones and is similar although 0.5 m - 1 m thicker and slightly more laminated than Member I. Member IV is represented by a second dolomitic sequence which could be considered as two units: the lower one (2.5 m) is characterized by laminated, often burrowed and mudcracked facies whereas the upper one (4.5 m or more) consists mainly of homogeneous and mottled facies which frequently contain carbonate nodules and intraclasts. Both, Member III and Member IV are well represented at Town Farm Bay and Isle La Motte (Figs. 9.25 and 9.32) whereas at South Hero these units are discontinuous and poorly exposed (Fig. 9.28). The stratigraphic correlation among the sections containing the upper contact or post-Beekmantown unconformity is presented in Figure 6.1. Neither the calcareous nor the overlying dolomitic lithofacies of the Carver Falls section (Fig. 9.20) appear to belong to Members III or IV, respectively. In addition, the partially laminated limestones located at the upper portion of the Boss Hogg's Quarry section (Fig. 9.21) do not seem to correlate with Member III since their associated underlying dolomitic lithofacies do not resemble the thicker bedded dolostones of Member II which crop out at Town Farm Bay or Isle La Motte (Figs. 9.21 and 9.25 or 9.32). However, these limestones of the Boss Hogg's Quarry may correlate with the laminated limestones that are exposed at the lower portion of the Carver Falls section. As a result of this, it is thought that the limestones occurring at the Carver Falls and Boss Hogg's Quarry sections may

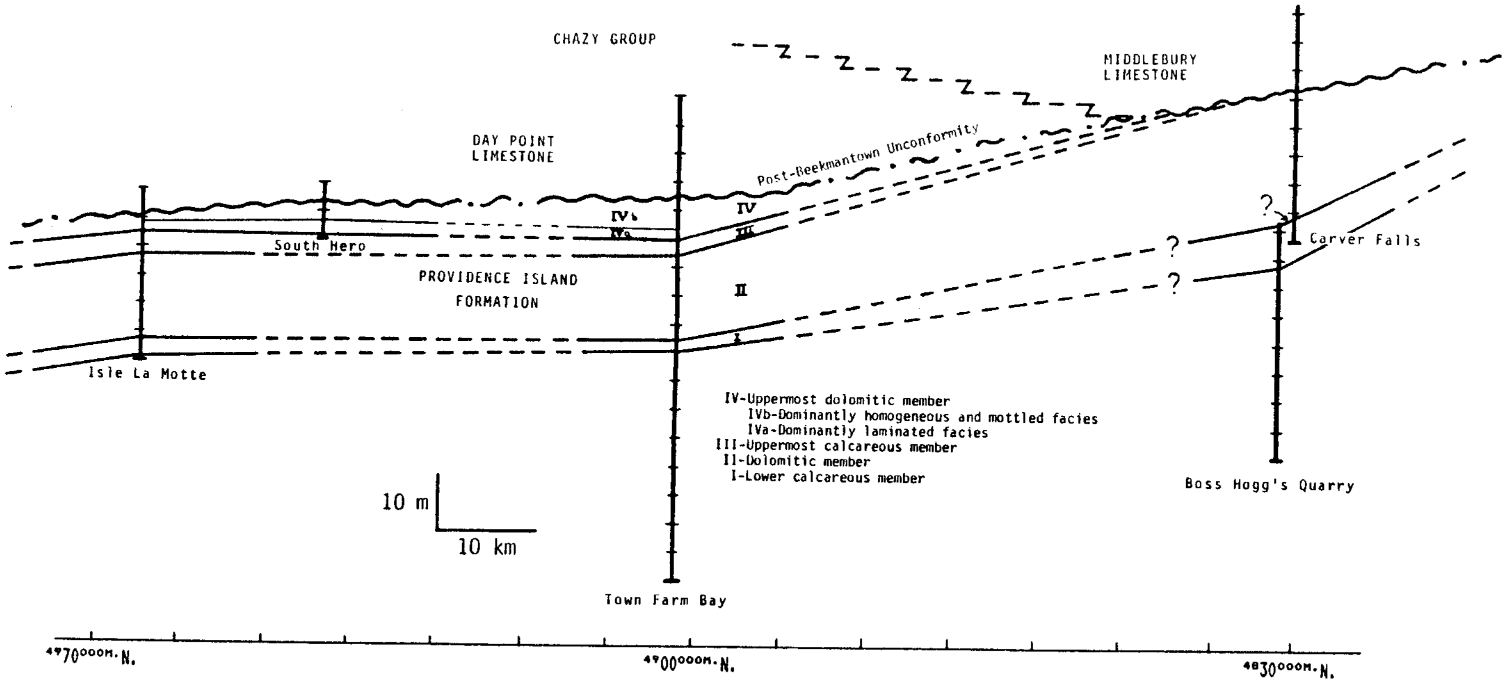

Fig. 6.1.- Correlation of the stratigraphic sections containing the upper contact of the formation or post-Beekmantown unconformity.

belong to the lower calcareous member of the formation (Member I) (Fig. 6.1).

The outcrops that do not contain the base or top of the formation are from south to north: Granville Public Fishing Site (localities A and B) (New York), Ticonderoga (New York), Shoreham (Vermont), East Shoreham (Vermont), Valcour (New York), Saranac River (New York), Beekmantown (localities A and B) (New York), and Napierville (Quebec). The outcrops of Shoreham and East Shoreham which lie above the Champlain Thrust (Fig. 1.1) may have been tectonically transported from east to west for more than 80 km (Rowley, 1982). The exact geographic location of these outcrops as well as the graphic representation of their mesured sections is given on the Appendix (9).

The correlation among all the sections not containing the top or base of the formation as well as the regional stratigraphic section or sections of the Providence Island Formation is difficult due to the existence of four problems. In order of importance these are:

a) The stratigraphic reconstruction of the section at Town Farm Bay is rather difficult due to the structural complexity of the outcrop. Here, the deposits are folded, thrusted, as well as intruded by a 1.7 m thick nepheline syenite dike. Several major thrusts and a major stratigraphic repetion of 14 m of the section have been recognized. Other minor stratigraphic repetitions have been observed (Figs. 9.8A,B and 9.25). For details on these features see chapter 9.2.8.

b) The dolomitic lithofacies of the southern section of the Public Fishing Site at Granville (locality A) and of the Member IV as seen at Isle La Motte resemble each other. However, a possible correlation among these lithofacies is not consistent with observations at the nearby Carver Falls section where the upper calcareous and dolomitic members of the formation are missing. The deposits of the Granville Public Fishing Site section (locality A) also resemble a group of dolomitic lithofacies of the other section adjacent at that outcrop (locality B). The deposits of the latter section are not characteristic of the upper portion of the formation as seen in the northern and central outcrops and hence, they are probably located on a lower stratigraphic position. A detailed mapping of the entire outcrop at the structurally-complex Granville Public Fishing Site could serve to identify a possible correlation among the two colunms recorded at this outcrop. The exact stratigraphic location of the section at locality A is critical for the correlation and regional interpretation of the Providence Island Formation. If this section belongs to the uppermost portion of the formation (Member IV) it implies that the thinning of the formation to the south (below) is mostly related to a thinning of the entire formation. However, if this section represents lower lithofacies of the formation, then, the thinning of the formation to the south may result from the downcutting of the overlying Post-Beekmantown

Unconformity.

c) The dolomitic lithofacies of the sections at Beekmantown (Figs. 9.30 and 9.31) resemble those of Member II which also crop out at the Isle La Motte section. However, they also resemble lithofacies of the lower portion of the structurally-complex Town Farm Bay section which appear to be in a lower stratigraphic position than the similar lithofacies of the Isle La Motte section.

d) The deposits of the Saranac River section (Fig. 9.29) resemble those that characterize Member IV (above). However, they also resemble a group of deposits of the Granville Public Fishing Site section (locality B) which seem to be located at a lower stratigraphic position (above). Hence, the exact stratigraphic position of the Saranac River section within the formation is uncertain.

Figures 6.2 and 6.3 show two possible correlations of all the sections of the Providence Island Formation depending on the stratigraphic position of the Granville Public Fishing Site Section (locality A). Because the post-Beekmantown unconformity seems to represent an important erosional surface (7.3), it is thought that Figure 6.2 is more probable than Figure 6.3. These figures also show the most probable correlation of the sections that do not contain the upper or lower contact of the formation. However, the stratigraphic position of these sections is still uncertain. Formation thicknesses are tentatively given

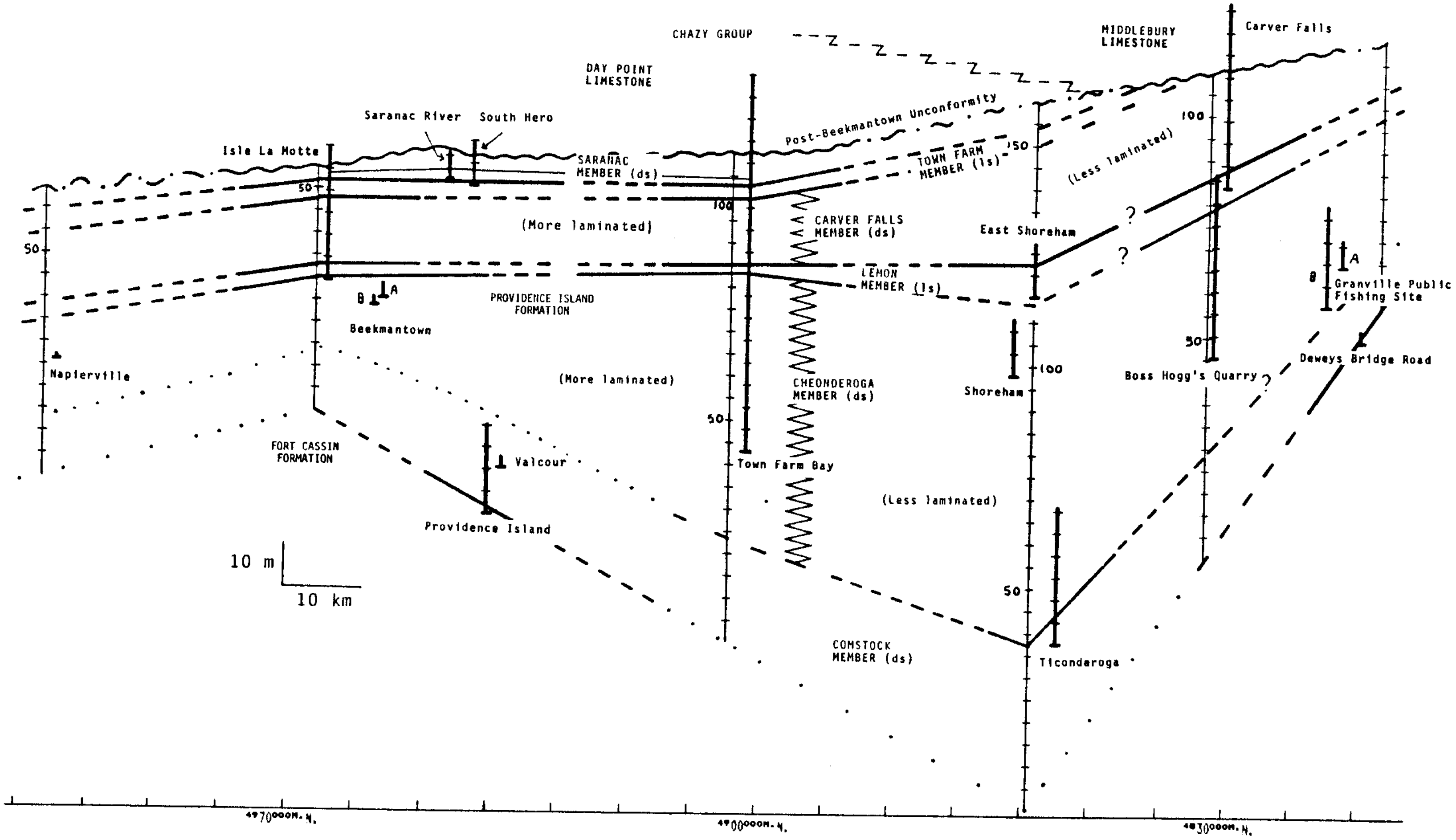

Fig. 6.2.- Possible correlation of all the measured sections of the Providence Island Formation. The proposed stratigraphic correlation of the sections not containing the lower or upper contact of the formation is thought to be the most likely.

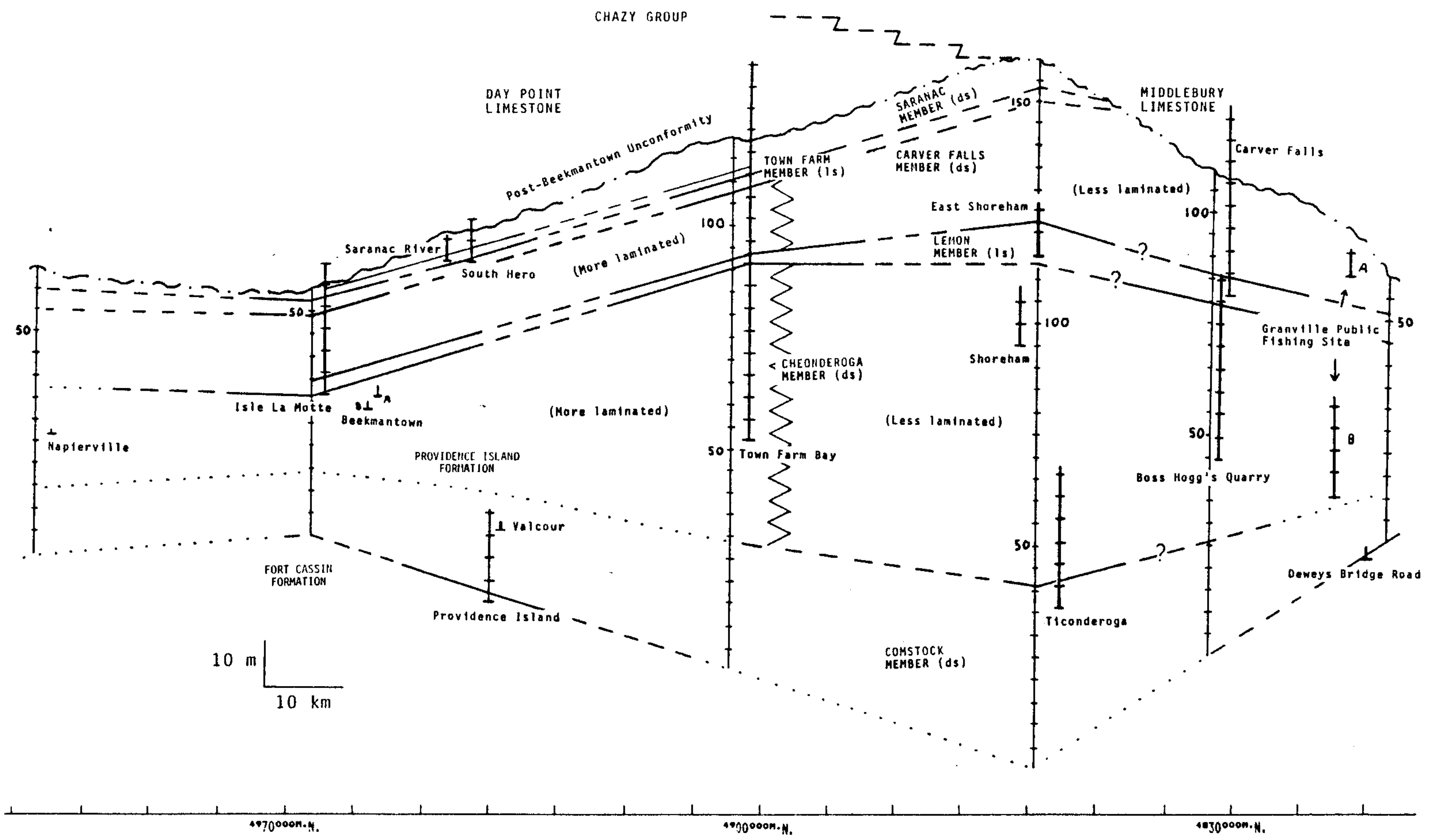

Fig. 6.3.- Alternative correlation of all the measured sections of the Providence Island Formation. This figure differs from Figure 6.2 due to a different stratigraphic correlation of the Granville Public Fishing Site Section (locality A).

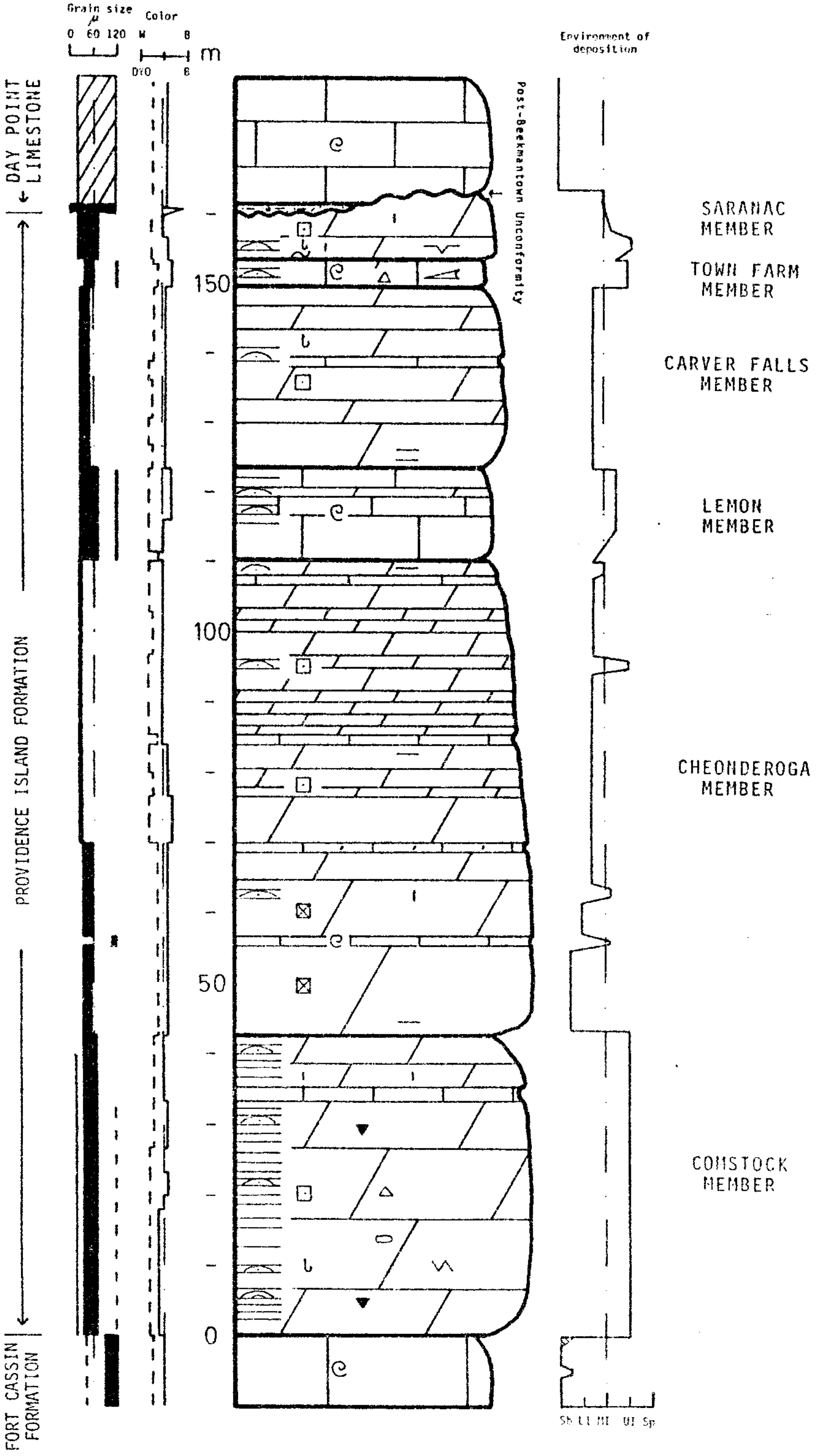

Fig. 6.4.- Possible stratigraphy of the Providence Island Formation at the area of East Shoreham, Vermont, based on the correlations presented in Figures 6.2 and 6.3. Legend is in Figure 9.16.

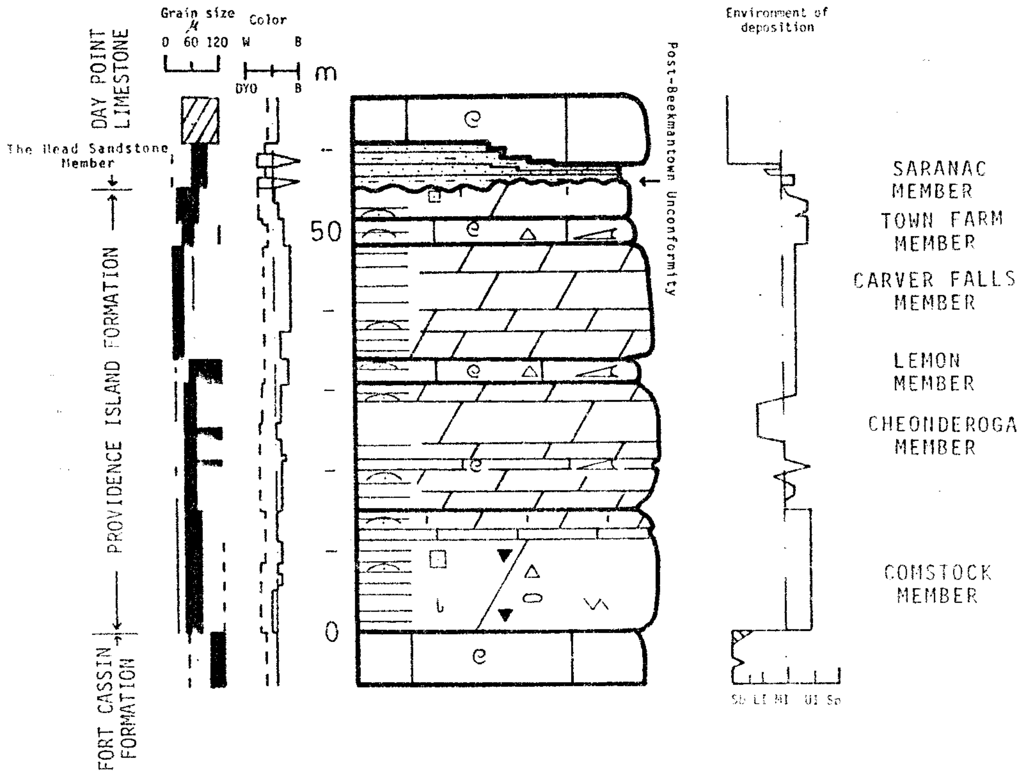

Fig. 6.5.- Possible stratigraphy of the Providence Island Formation at the area of Isle La Motte, Vermont, based on the correlations presented in Figures 6.2 and 6.3. Legend is in Figure 9.16.

in these figures based on documented data from other authors (e.g. Fisher, 1977) and personal calculations.

Figures 6.4 and 6.5 show the possible stratigraphy of the Providence Island Formation at the areas of East Shoreham, Vermont, and Isle La Motte, Vermont, based on the correlations presented in Figures 6.2 and 6.3. Members are tentatively proposed (Figs. 6.2 to 6.5).

6.3 Lateral variations and related stratigraphic units

The Providence Island Formation pinches out and disappears south of Fort Ann, New York. The percentage of shale seams or beds within the formation increases to the north. This increase is expected because of the lateral change of facies of the Providence Island Formation into the shaly, calcareous, and dolomitic lithofacies of the upper Bernahois Formation to the north in southern Quebec (Clark, 1952). The Providence Island Formation correlates with the upper portion of the Ogdensburg Dolostone which crops out to the north-west of the area of study along the St. Lawrence Valley in the vicinity of the town of Massena, New York (Fisher, 1977).

Welby (1961) has suggested that the limestone content of the formation increases towards the east. This observation has to be made with care since outcrops are more abundant and generally more continuous at the eastern margin of the Champlain Valley. Hence, is more probable to find more exposures of the calcareous units or lithofacies in the eastern rather than the western part of the outcrop belt of the formation. Nevertheless, an eastward increase in the limestone content of the formation is to be expected since the Providence Island Formation and the eastern limestone and marble-bearing Beldens Formation are correlatives (Welby, 1961). The stratigraphic relationships between the Providence Island Formation and the upper Bernahois, upper Ogdensburg, and Beldens Formations are uncertain due to lack of intervening surface exposure.

6.4 Thickness

It is speculative to estimate the thickness of the formation at different geographic locations since the regional stratigraphic correlation among all the sections has not been obtained. By consideration of the topography, average dip, and the approximate location of the upper and lower contacts, it is tentatively proposed that the thickness of the Providence Island Formation in the area of East Shoreham is approximately 160 m (525 ft). However, there are indications in this area that folding and faulting might influence that figure. The estimated thickness at East Shoreham closely matches the 143 m (470 ft) suggested by Brainerd and Seely (1890) in the same locality.

6.5 The post-Beekmantown unconformity

As has already been stated, the upper contact of the formation is represented by the post-Beekmantown unconformity which is well observed at the Isle La Motte, Town Farm Bay and Carver Falls sections. This unconformity has been also called the Knox unconformity (Rickard, 1973). However, some workers refer to the knox unconformity as the Chazy-Black River Group contact. Therefore, the term post-Beekmantown unconformity seems appropiate to use in order to avoid confusion.

At the scale of an outcrop, this unconformity is apparently a paraconformity; that is, no erosion surface is discernible or significant at the break, and the beds above and below it are parallel. However, at a regional scale, the post-Beekmantown unconformity appears to reflect an extensive erosive event. For details on this discussion see chapter 7.3.

The exact location of the unconformity at the Isle La Motte section is not easily recognized. Here, the unconformity is represented by a scoured surface which separates the dolomitic lithofacies of the Providence Island Formation from the basal fine- grained impure sandstones of the overlying Chazy Group (Figs. 3.5 and 9.32). These latter deposits alternate, with increasing frequency, with higher, progressively coarser-grained and less impure sandstones and then with arenaceous limestones and limestones. The scoured surface observed at the unconformity is not considered a significant erosive surface since identical structures have been observed within the dolomitic beds of the Providence Island Formation (Fig. 3.6). At the Town Farm Bay section the unconformity is sharp due to the sudden appearance of a 20 cm shale bed above the dolostones of the Providence Island Formation. This shale contains a quartzite conglomerate intercalation which probably represents a channel-fill deposit (Figs. 6.6 and 9.25) and is overlain by quartz-arenites, more shales, and fossiliferous limestones that belong to the Day Point Limestone (Chazy Group). At the Carver Falls section the unconformity is also apparently represented by a sharp depositional contact. The thin bedded, homogeneous and mottled dolostones of the Providence Island Formation here pass abruptly into the highly fossiliferous, probably subtidal, wackestone and packstone beds of the Middlebury Limestone (correlative with the Crown Point Limestone of the Chazy Group; Welby, 1961). At this section the lower deposits of the Chazy Group (or Day Point Limestone) are missing. At the South Hero section the unconformity is covered by soil but both the dolostone and the relatively pure dolomitic sandstone beds of the Providence Island Formation and Chazy Group, respectively, can be observed.

The post-Beekmantown unconformity may correlate with the post-Knox unconformity which is located in the Copper Ridge district, East Tenessee (Churnet and others, 1982) since both unconformities separate rocks that are similar in age and characteristics. The implications of the post-Beekmantown unconformity are discussed in chapter 7.3.

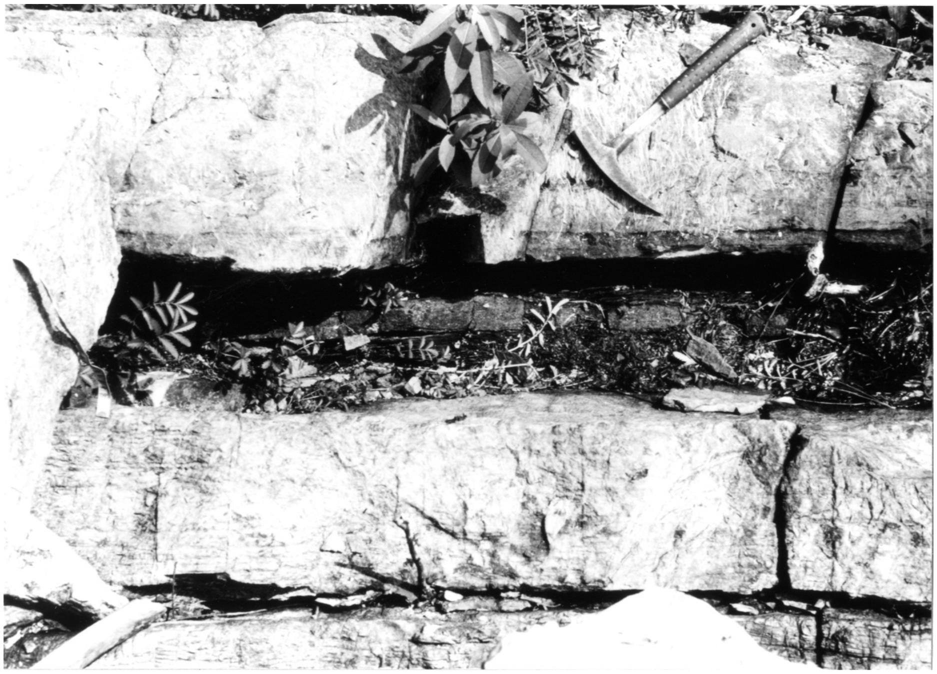

Fig. 6.6.- Post-Beekmantown unconformity at Town Farm Bay Section (91 m). The unconformity separates a partially laminated dolostone bed of the Providence Island Formation (lower part) from a shale bed of the overlying Day Point Limestone (low relief; just above center). The shale contains a channel-fill deposit formed by a quartzite conglomerate.

7.- REGIONAL INTERPRETATION

7.1 Possible paleogeography

The characteristics of the rocks suggest that the lithofacies of the Providence Island Formation have been deposited mainly on broad semiarid tidal mud flats and, occasionally, in adjacent subtidal environments with restricted marine or low energy hydraulic conditions (Fig. 2.2). A tidal mud flat setting is inferred mainly by the muddy nature of the original sediment (2.3) and by the presence of mudcracks (3.2) as well as dessicated stromatolites (2.4). The muddy nature of most deposits of the formation, the apparent low diversity of the biota (2.3 and 2.8), and the presence of planar stromatolites (2.4), supports the hypothesis of a low energy hydraulic zone (Z zone of Irwin, 1965) for the original depositional environment (Wilson, 1975; Kendall and Skipwith, 1968b). Semiarid and, perhaps, arid climate is inferred by a) the absence of K-feldspar and plagioclase hydrolization (2.11), b) the presence of isolated evaporites or their pseudomorphs which may suggest either a brackish flow of groundwater from a mainland (James, 1984) and/or the supratidal sabkha or that the salinities of brines that formed on the sabkha are not very high (5.2) and, c) paleolatitude (below). The shoreline in the area of study appears to have been approximately oriented in the north-south or north-northeast direction. This interpretation is based on observations on both the elongation of domal stromatolites observed at the Providence Island section (2.4) and the ripples found at the Isle La Motte section which may indicate an approximate orientation of the local shoreline of N 40^0 E and a southeast local offshore direction (3.4). This observation is consistent with the presence of correlative deeper water deposits, such as the Beldens Formation to the east of the Providence Island Formation outcrop belt.

The presence of occasional muddy subtidal deposits (2.3) and restricted marine conditions in the depositional environment suggests that the tidal flats probably occurred shoreward of a shallow lagoon, perhaps, behind some kind of protective physical barrier. However, as has been previously stated, the tidal flats were still affected by spring tides and severe storms (2.4, 2.8, and 5.2). Such interpretation is consistent with observations in both, modern arid carbonate tidal flats occurring in low energy hydraulic zones, such as those of the Persian Gulf (Shearman, 1963; Kendall and Skipwith, 1968a,b) and in Early Ordovician deposits of the Appalachian Region (Levesque and others, 1977). Levesque and others (1977) have suggested that the Early to Medial Ordovician carbonate lithofacies of the northern maritime Appalachians are low energy deposits, probably due to the existence of a colonial sponge (?) reef barrier along the platform margin. Other possible reef barrier at this time could have been algal mounds (James, 1984). Another alternative is that restricted marine conditions were achieved due to the existence of a broad shallow sea, somewhat similar to an epeiric sea, adjacent to the tidal flats. Extensive wave action would only occur at the margin of this shallow sea with the deep sea.

The tidal flats, lagoon, and possible barrier or seaward margin of the lagoon are believed to be parts of a vast continental shelf which occupied much of the eastern half of the United States during the Late Cambrian and Early Ordovician (Harris, 1973; Rickard, 1973). On the other hand, it is thought that to the west of the tidal flats there is an eroding emergent land where the Grenville basement, or Cambrian-Ordovician deposits underlying the Providence Island Formation, or both, are exposed. This interpretation is based on a) the inferred presence of aeolian material whose primary source area appears to be the Precambrian Grenville basement (2.11), b) the possible flow of brackish groundwater from a mainland (5.2), and c) the fact that tidal flats commonly form belts that parallel emerging reliefs in modern settings (Bathurst, 1975; Friedman and Sanders, 1978).

Unfortunately, no conclusive evidence has been found in the lithofacies of the Providence Island Formation to determine the exact nature of the possible barrier.

Based on the Early Ordovician paleogeographic maps proposed by Smith and others (1981) the Lake Champlain area was located approximately at 15^0 S latitude and the North

American continent as a whole had an approximate clockwise rotation of 50^0 with respect to its present position. A latitude of 15^0 S is consistent with an interpretation of semiarid climate in the environment of deposition of the Providence Island Formation because recent tropical dry climates are concentrated between latitudes 15 and 35^0 + (Trewartha and Horn, 1980). A general picture of the tidal flats and of their possible associated environments is shown in Fig. 7.1.

7.2 The tidal flats

Most lithofacies of the formation seem to have originated in both lower and upper intertidal zones of the tidal flats (Figs. 9.17 to 9.33). The lower intertidal zone appear to be dominated by burrowing organisms that partially homogenized the sediment and thus produced mottled structures (2.3). Algal-laminated sediments form in the upper intertidal zone, where the domal structures appear to be restricted to the seaward fringe of this area and the planar varieties seem to dominate most of this upper intertidal environment (2.4). The adjacent subtidal and supratidal zones occur only sporadically within the formation and are characterized by the presence of completely burrowed or homogenized sediments (subtidal) and homogeneous beds containing abundant evaporites or their pseudomorphs, terrigenous material as well as structures that are associated with the former presence of evaporites (supratidal) (2.3). The distribution of these facies is presented in Figure 7.1. A facies distribution of this type is analogous to that shown by many tidal flats of the Trucial Coast of the Persian Gulf (Shinn, 1983). For this reason, it is thought that the Providence Island Formation represents a Canadian-age analogue to recent tidal flat carbonates of the Persian Gulf.

It has been often suggested that the main source of the tidal flat carbonate sediments is the adjacent off-shore marine zone. These sediments are brought onto the flats by storms rather than by daily tides (James, 1984). Sporadic floodings of the flats have been previously inferred by the presence of intercalations of skeletal limestones within the other carbonate lithofacies of the formation (2.8) or, perhaps, by intercalations of mottled horizons within the laminated facies (2.4). The variability among the deposits of the Providence Island Formation within the same hydraulic zone (Z zone) is probably due mostly to fluctuating intertidal, climatic, and diagenetic conditions rather than to small tectonic movements since the characteristics of the deposits of the Providence Island Formation indicate that the area was tectonically stable during the time of deposition of the formation (below). Lateral variations in thickness, such as the southward thinning of the upper calcareous unit of the formation may indicate a) that depositition in the tidal flats was occasionally or frequently not uniform, b) a lateral shift in the calcareous

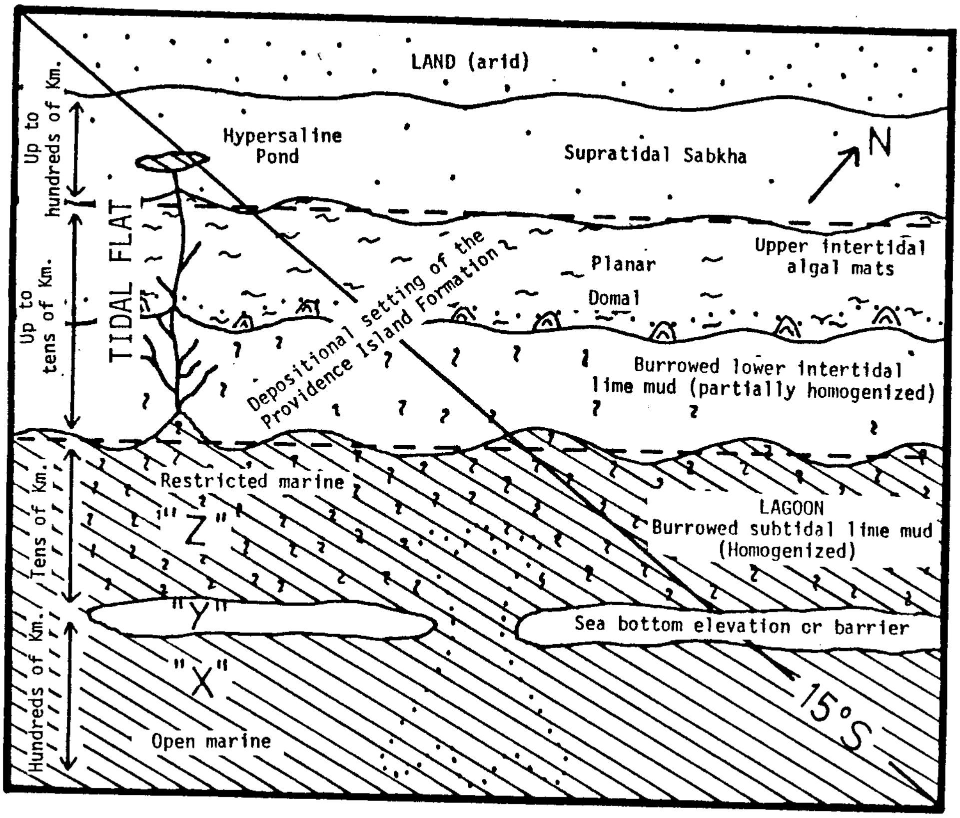

Fig. 7.1.- Plant view showing approximate paleogeography in the Northern Appalachian Region during the Early-early Middle Ordovician. The paleogeography is interpreted from the lithofacies of the Providence Island Formation and from data obtained by other authors in this region. Boxed area (dashed line) represents the depositional environments of the Providence Island Formation.

facies, or c) differential compaction of the calcareous facies at different localities.

The tidal flats are thought to be broad, perhaps more than 80 km wide at certain areas. This interpretation is supported by the presence of tidal flat deposits at the sections of Shoreham and East Shoreham, Vermont, which lie above the Champlain Thrust and may have undergone an east-west tectonic displacement greater than 80 km (6.2).

7.3 Tectonic and paleogeographic implications. The post-Beekmantown unconformity

As has already been stated, the Providence Island Formation appears to thin markedly at the south of its outcrop belt and seems to be entirely absent south of Fort Ann, New York. This considerable variation in thickness could be related to 1) a marked differential subsidence of the area of study, 2) a progressively greater depositional hiatus to the south, 3) regional post-depositional erosion that cuts into lower units of the formation towards the south, or 4) a combination of any of these events. The exact stratigraphic position of the Granville Public Fishing Site (locality A) Section (9.2.2) seems to be critical for knowing the most important factor that contributed to the thinning of the formation to the south. Nevertheless, it is thought that there was not any marked differential subsidence in the area of study at the time of deposition of the Providence Island Formation since the lithofacies of this formation do not show any evidence that reflects disturbance in the development of the tidal flats. The intertidal character of most of the lithofacies of the Providence Island Formation implies that this formation is not a shallowing or deepening-up sequence. This observation may be used as evidence that its depositional environments developed on a tectonically stable passive margin that subsided slowly at a near constant rate. If the accumulation of the Providence Island Formation results from a gradual rise of sea level, then tectonic stability is inferred in the area. If the slow subsidence then occurred, the subsidence rate probably equaled the accumulation rate since the formation is not a shallowing- or deepening-up sequence. If it is true that the time span for the accumulation of the Providence Island Formation is about 5 m.y. in the area of Ticonderoga, New York (Fisher, 1977) then, the accumulation rate (or subsidence rate) of the Providence Island Formation is thought to be about 6 cm/1000 years assuming also that (a) the thickness of the formation at Shoreham, Vermont (close to Ticonderoga), is about 160 m (6.4), (b) the formation has compacted by about 50% (5.6), and (c) there are not significant hiatuses or unconformities within the formation. A value of 6 cm/1000 years in a passive margin is a relatively slow rate of subsidence for this tectonic environment (Demicco and Hardie, 1981). Because the upper portion of the formation has been partially eroded (below), the real subsidence value could be higher. However, the characteristics of the lithofacies of the formation reflect tectonic stability of this portion of the shelf and, hence, it is thought that a subsidence rate 6 cm/1000 years is about right for this area during the time of deposition of the Providence Island Formation (middle and late Cassinian to middle Whiterockian).

Because the characteristics of most or all the deposits of the Providence Island Formation reflect tectonic stability in their environment of deposition, it is thought that the tectonic evolution of northern and southern localities is analogous to central ones. Hence, the most important contributing factor to the variation in thickness of the formation seems to be progressive erosion of the formation from top to bottom to the south of the outcrop belt. This interpretation is supported by the fact that the uppermost unit of the formation (unit IVa of Member IV: homogeneous, mottled and, to a lesser extent, laminated dolostones) which is 4.5 m thick at the central section of Town Farm Bay is only 0.5 m thick at Isle La Motte, Vermont (north), and completely absent at Carver Falls, Vermont (south) (Fig. 6.1). Because the intimately associated underlying laminated and, to a lesser extent, homogeneous and mottled dolostones do not show variation in thickness or facies from central to northern localities (Fig. 6.1) there is some reason to believe that the uppermost homogeneous and mottled dominated facies have been eroded in the north and south. Consequently, it is thought that the absence of the upper part of the formation, as well as the calcareous Member III and an undetermined amount of underlying deposits (presumably of Member II; 6.1) at Carver Falls, Vermont, where the post-Beekmantown unconformity is displayed, is probably related to the same, but more extensive, erosive event. This history probably resulted from a period of emergence of this portion of the shelf and is represented by the post-Beekmantown unconformity. It is undetermined at present if the upper contact of the formation may represent, in part, a hiatus. Rickard (1973) attributes the post-Beekmantown unconformity to a period of uplift and subsequent erosion of the continental shelf. However, on the basis of trilobite and conodont-based correlations of the Valhallfonna Formation (Arenigian-Llanvirnian equivalent) in Spitsbergen (the far northeastern extension of the Paleozoic North American continent), Fortey (1980) has suggested that the sedimentary "gap" between the Canadian and the Champlainian times in western Vermont, which is indicated by the post-Beekmantown unconformity, represents a period of marine regression over almost all the North American platform.

Observations of the deposits overlying the unconformity suggests that the post-Beekmantown unconformity may represent an event that also controlled the deposition of the lower part of the Chazy Group. The basal clastic beds of this group thin and disappear toward the south in the area of study. The same thing appears to happen to the lower limestone beds of the Chazy Group (Day Point Limestone) which immediately overly the basal clastic deposits. These limestones which are exposed at the northern sections (e.g. Isle La Motte, Vermont) are missing at southern localities (e.g. Carver Falls, Vermont).

In order to know the exact significance of the post-Beekmantown unconformity the depositional environments of all the rocks underlying and overlying the unconformity have been interpreted using documented data from authors who have described such rocks. As a result of this, it is believed that the post-Beekmantown unconformity has other important paleogeographic and, perhaps, tectonic implications. All the Cambrian-Early Ordovician carbonates inmediately below the unconformity appear to have been deposited in quiet shallow subtidal to supratidal environments. However, the contiguous overlying deposits of the Chazy Group reflect normal marine conditions with increasing depth until the end of the time of deposition of the Crown Point Limestone where intertidal conditions are achieved again (Fig. 1.2). This abrupt change of the conditions of deposition represented by the unconformity is probably related to a period of emergence or, perhaps, a depositional hiatus (above) followed by a major marine transgression, a marked subsidence of this portion of the shelf, or a combination of these two events. In any case, the transgression or the subsidence seems to overcome the progradation of both the tidal flats represented by the Providence Island Formation and the inferred offshore protective barrier. A somewhat similar situation occurred at the end of the time of deposition of the Chazy Group which is characterized by the presence of another unconformity, the post-Chazy unconformity. Here, the overlying Black River and Trenton units record transition to deeper water and turbidite sequences. However, in this case intertidal conditions are not restored again. As a result, it is thought that this second change of the conditions of deposition represented by the post-Chazy unconformity may mark the passage of a crustal flexural bulge in the area of study as Taconic collisional events began (Bradley and Kusky, 1986). Because it seems that there is a more drastic change of the sedimentary facies after the time of deposition of the Chazy than of the Beekmantown Group in the Champlain Valley, it is thought that the Knox unconformity which marks the top of the Beekmantown Group in the Mohawk Valley correlates with the post-Chazy unconformity of the Champlain Valley.

As stated before, the post-Beekmantown unconformity is possibly related with the post-Knox unconformity located in the Copper Ridge district, East Tennessee (Churnet and others, 1982) (6.5).

7.4 Late / post-diagenetic geological events as inferred from the outcrops of the Providence Island Formation

Based on the cross-cutting relationships of the late / post-diagenetic structures which are especially well displayed at the outcrop of Town Farm Bay, the following time sequence of late geological events can be inferred:

a) Load induced dissolution: This process produces sub-horizontal stylolites which develop preferentially at the contact between carbonates and shale interbeds.

b) Folding: Folds trending north-northwest (Figs. 7.2 and 9.8A,B) as well as sub-vertical stylolites probably result from regional, near-horizontal shortening.

c) Thrusting: Continued sub-horizontal shortening caused thrust-faulting which preferentially developed at the shale interbeds or sub-horizontal stylolitic surfaces. The thrust-faults frequently cut through the hinges or truncate the above mentioned folds (Fig. 7.2). Slickensides, calcite veins, and shale fragments are common features of the thrust planes (Fig. 7.3).

d) Intrusion of igneous dikes: Dikes cut through all the above mentioned structures. Only one dike has been observed at Town Farm Bay (Fig. 9.8B), Vermont, and it has a porphyritic texture and the composition of a nepheline syenite, which is close to that of a foyaite.

Folding and thrusting probably formed during the same tectonic episode (presumably the Taconic Orogeny) but, as has been inferred above, not within the same tectonic phase. Because of thrusting, some outcrops of the Providence Island Formation may have undergone large displacements (6.2). The intrusion of the nepheline syenite dike represents a feature

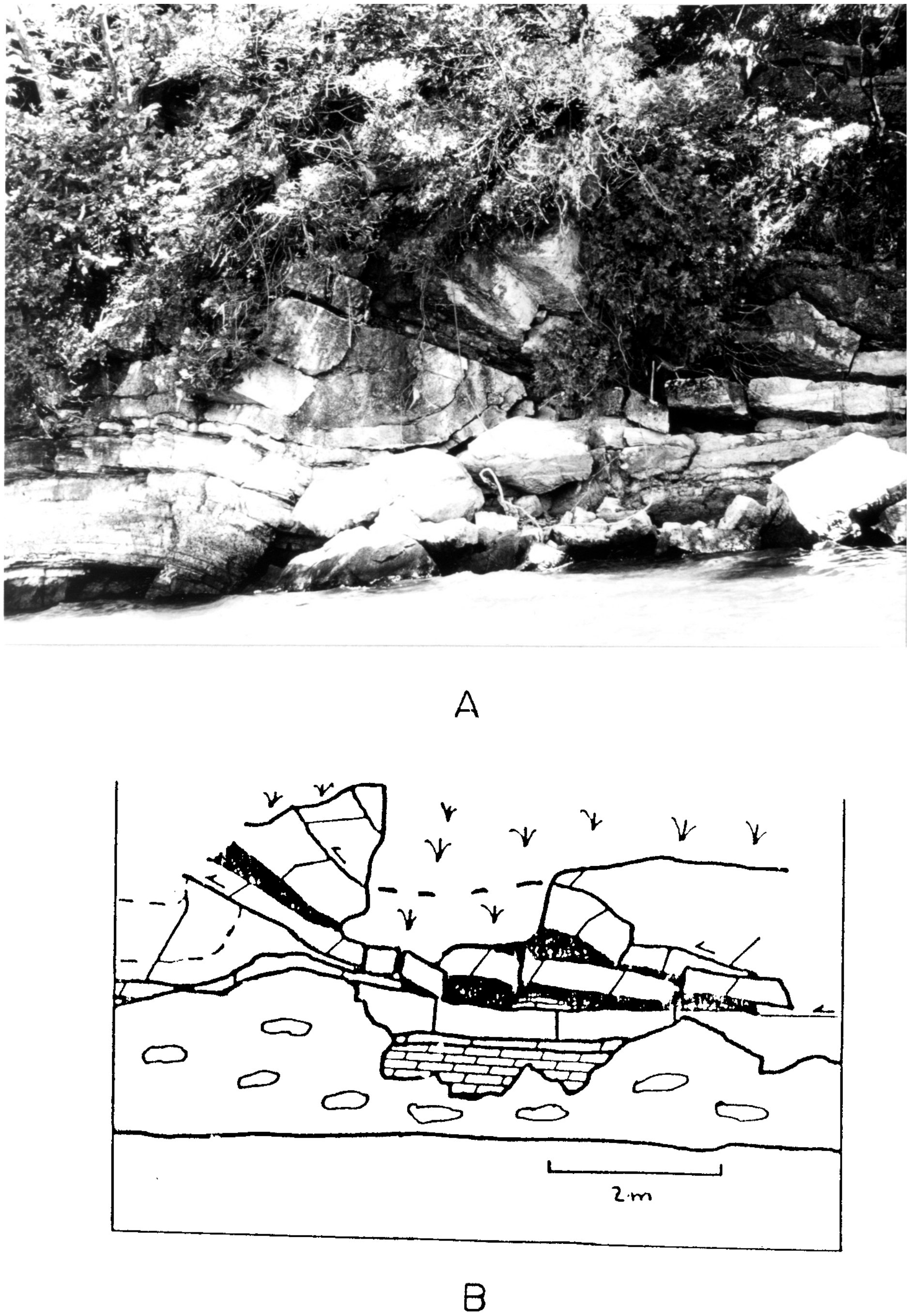

Fig. 7.2.- A-B) Fold and thrust-fault affecting the deposits of the Providence Island Formation near the Champlain Thrust. Note that the thrust-fault truncates the fold. Town Farm Bay Section (11 m).

Fig. 7.3.- Specimen taken from a thrust-fault plane which show calcite veins (white; below) and rotated (?) shale fragments (black; lower right hand corner). Town Farm Bay Section (62 m).

of a later tectonic event that probably occurred during the Late Jurassic-Early Cretaceous (Fisher, 1968).

The presence of chlorite and sericite in the shales (2.10) may suggest a greenschist facies, chlorite zone, metamorphism for the area of study. However, the presence of other argillaceous minerals which do not show metamorphic effects (e.g. recrystallization) suggests that the metamorphism is low grade. The relative timing of this metamorphism is presumably Taconic.

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9.- APPENDIX. OUTCROPS AND STRATIGRAPHIC SECTIONS

9.1 General comments

The best exposed outcrops, in both continuity and size, are located on the shores of the central and northern parts of Lake Champlain in Vermont (Town Farm Bay, eastern shore of Providence Island, and south shore of Isle La Motte). Within the lowlands or in adjacent areas, the outcrops are generally scarce and poorly exposed (Deweys Bridge Road, Comstock, New York, and Shoreham, Vermont) with a few exceptions (East Shoreham, Vermont, and South Hero, Vermont). The only well exposed outcrops within the Champlain lowlands or adjacent region are found in riverbank outcrops (Granville Public Fishing Site, New York; Carver Falls, Vermont; Ticonderoga, New York; and Saranac River, New York), quarries (Boss Hogg's Quarry, West Haven, Vermont; and Beekmantown -locality A-, New York), road cuts (Beekmantown -locality B-, New York), and railroad cuts (Valcour, New York).

In southern Quebec, outcrops of the Providence Island Formation, referred to the upper part of the Bernahois Formation, seem to be very scarce and poorly exposed. Only one meter in Napierville has been recorded in this work. This is due to the fact that the bedrock is largely covered by later Pleistocene sediments (as in eastern New York and western Vermont) and that shale is an important lithology of the formation (Clark, 1952). Based on the characteristics of the Bernahois Formation, as presented by Clark (1952), the other fifteen sections that have been examined in southern Quebec seem to correlate with lower formations of the Beekmantown Group of eastern New York-western Vermont. Therefore, these sections are not presented in this study.

The type section of the Providence Island Formation has been considered to be located at East Shoreham, Vermont (Brainerd and Seely, 1890), but the section is not well exposed here and is only 13 m thick. The Isle La Motte section is considered the most representative section due to its good exposure, continuity, and lack of deformation. However, although the Town Farm Bay section is structurally complex, this section probably provides the most complete sequence observed in the Providence Island Formation.

9.2 Outcrops and sections

9.2.1 Deweys Bridge Road, Comstock, New York

At this locality only 3 m of deposits have been recorded (Fig. 9.17). The lower contact of the Providence Island Formation is well displayed here (Fig. 9.2 and 9.17). However, the formation is badly exposed here because the dip of the strata almost parallels the topographic slope. To the north-west the outcrops are scattered in the woods and the stratigraphy is difficult to reconstruct. The beds occasionally form ridges.

9.2.2 Granville Public Fishing Site, New York

This outcrop represents a good exposure of the Providence Island Formation. However, stratigraphic control has not been achieved along the entire outcrop due to its structural complexity (Fig. 9.3). As a result of this, two sections have been constructed (A and B; Figs. 9.18 and 9.19, respectively). The southern section (A) is about 6 m thick and includes mudcracked, laterally linked hemispheroids (LLH-C of Logan, 1964) at 3.20 m (Fig. 2.5). The cracks have developed in the concavities between the domes. The internal concentric lamination of the stromatolites is exposed due to later weathering processes (Fig. 2.9). For additional information on this structures see chapter 2.4. Analogous algal domes occur 2.30 m above the base of the section. Such structures, diagnostic of relatively moderate energy in the middle intertidal zone, are associated with ripples. The northern section (B) is 23 m thick and contains deposits that have been mainly deposited between the subtidal-intertidal boundary and the middle intertidal zone. As has already been stated, the exact stratigraphic position of both, the southern and the northern sections within the formation is critical for the regional correlation of the Providence Island Formation and hence, for the paleogeographic and tectonic implications of the formation (6.2 and 7.3).

The Metawee River is believed to run through an important fault since it is the site of a sharp contact between the dolostones of the Providence Island Formation with black shales which presumably belong to the Trenton Group (Fig. 9.3). The course of the river frequently does not conform the strike of the dolostones. Therefore, it seems that folding and faulting or thrusting did not occur simultaneously during the same orogenic phase or episode. This interpretation is consistent with the time sequence of post-diagenetic events that have previously been discussed (7.4).

9.2.3 Carver Falls, West Haven, Vermont

The formation is well exposed and a section, 32 m thick, has been mesured here (Fig. 9.20). The beds strike to the north-east and dip moderately to the south-east (Fig. 9.4A). The section is mainly characterized by the presence of both a calcareous member at its base and the upper contact or post-Beekmantown unconformity (Figs. 6.1 and 9.20). The deposits inmediately below the calcareous member are not accessible below the brink of the falls. The limestones probably represent the lower (Member I) of the two calcareous members observed in the Providence Island Formation (6.2). In addition, it seems that these limestones correlate with those found in the upper portion of the nearby section at Boss Hogg's Quarry, West Haven, Vermont (6.2) (Fig. 6.1). A problematical structure occurs at 19.5 m above the base of the mesured section. A limestone bed is in sharp contact here with a dolostone bed. This feature is interpreted as resulting from the presence of two small folds, a syncline and an anticline. This interpretation is based on the careful analysis of this part of the outcrop and on the presence of better displayed analogous structures at the outcrop of Town Farm Bay, North Ferrisburg, Vermont. At this level of the section a lenticular limestone bed is also in sharp contact with a dolostone bed. This feature seems to be related to the presence of a small fault or thrust. Similar structures that have originated in this manner can be observed at the nearby Boss Hogg's Quarry section.

In the eastern part of this outcrop the Providence Island Formation is overlain unconformably by the Middlebury Limestone of the Chazy Group (6.5) (Fig. 6.1 and 9.20). The exact location of the unconformity has been inferred upon careful observation of the deposits at this part of the outcrop. In addition, the basal, frequently laminated skeletal limestones of the Middlebury Limestone resemble in the field the skeletal laminated limestones of the Providence Island Formation that are sometimes found at other sections. Because it is unlikely that the unconformity separates similar limestone beds in both formations, it is thought that the unconformity is located inmediately above the uppermost dolostone bed of the section (26.75 m; in Fig. 9.4A) which is located about 25 m to the west from the dam.

The limestones at the base of the section are laminated by the probable presence of planar stromatolites which also display planar and sub-spherical to irregular fenestral cavities (2.7 and 3.5) (Figs. 9.20 and 3.12). In contrast to the laminated character of the limestones, the overlying dolostones are mostly mottled (2.3).

Probable evidence of downward dolomitization is observed at 21 m above the base of the section where a bed grades from a dolomitic limestone at the bottom to a calcareous dolostone at the top (Fig. 5.1). Detailed information on this process is given in chapter 5.2.

The lowest coral fragment was noted in the Middlebury Limestone at 42 m (Fig. 9.20).

9.2.4 Boss Hogg's Quarry, West Haven, Vermont

A westerly view from the entrance of the quarry shows that the quarry cuts through a syncline, an anticline which seems to have a fractured hinge, another syncline, and a thrust-fault. All of these features trend north-northeast (Fig. 9.4B). The beds strike to the north-northeast and generally have a moderate to strong dip to the east. The section, 41 m thick, consists mainly of dolomitic lithofacies and it is significant that a calcareous member (probably Member I, Fig. 6.1) occurs in its upper portion (Fig. 9.21). This member is folded by the syncline located at the main entrance of the quarry. As noted above, this calcareous member appears to correlate with the calcareous member of the nearby Carver Falls section (Fig. 6.1). The most significant features found in the calcareous lithofacies and, probably in the entire outcrop include a cross-bedded deposit at about 37 m in the section that probably features rippled surfaces that were carpeted by algal mats (3.4) (Fig. 3.10A,B) and a bed composed almost entirely of intraclasts at about 39 m in the section (3.3). These features which are located along strike at both sides of the main entrance of the quarry have not been observed in the other sections of the formation.

9.2.5 Ticonderoga, New York

Thirty-one meters of rock have been recorded at this outcrop (Fig. 9.22). The strata are not easily accessible due to their exposure on a steep slope which is covered by abundant loose mineral and organic materials. The beds strike to the northwest-west and dip gently to moderately to the north (Fig. 9.5).

9.2.6 Shoreham, Vermont

Three sections have been described at this outcrop. They have been designated, from west to east, A, B, and C (Fig. 9.6A). The local stratigraphy has been reconstructed in a north-northwest trending, south-plunging anticline (Figs. 9.6B and 9.23).

The beds strike generally to the north-northeast and show a strong dip to the east or west at either sides of the anticlinal axis. The offset of the small topographic ridge shown in Figure 9.6A is probably due to the presence of a normal fault.

This outcrop as well as the one at East Shoreham, Vermont (below) lie above the Champlain Thrust (Fig. 1.1) and, hence, they possibly have been tectonically transported from east to west for a considerable distance (6.2).

9.2.7 East Shoreham, Vermont

The section at this locality has been considered the type section of the Providence Island Formation (Brainerd and Seely, 1890). However, it is believed that this section is not the most representative of the formation since the deposits are not well exposed here and only are about 12 m in thickness (Fig. 9.24). The beds strike approximately to the north and dip strongly to the east (Fig. 9.7).

The presence of a calcareous unit at the base of the section is significant, but it is uncertain if it correlates with either of the two calcareous members that have been recognized in the formation. There is also the possibility that this unit may represent a third calcareous member within the formation.

9.2.8 Town Farm Bay, North Ferrisburg, Vermont

The rock exposure at this locality is in a structurally complex thrust-repeated section. It represents the largest exposure of the Providence Island Formation and about 110 m of deposits have been recorded, 91 m corresponding to the Providence Island Formation and the rest to the overlying Day Point Limestone (Fig. 9.25). Underlying lithologies as well as thrust-repeated deposits are exposed to the north. However they have not been described due to the abundance of thrust faults in this part of the outcrop (Fig. 9.8A). The beds strike generally to the north-northeast and dip moderately to the east.

The measured section shows several major thrust faults, numerous bedding-plane faults with apparently minor translational throw, several parasitic folds, and an igneous dike (Figs. 9.8A,B, 9.25, 7.2A,B and 7.3). The slickenside striations found in two minor thrust faults at 38 m and 74 m (Fig. 9.25) plunge 50^0 and 25^0 to the southeast, respectively. These structures suggest a displacement of the rocks above the thrust surfaces to the west-northwest in the directions N 43^0 W and N 67^0 W, respectively. The folds also show variations in orientation but their general trend is to the northeast and their plunge usually ranges between 7^0 and 18^0 to the north (Fig. 9.8A). The igneous dike cuts through the section at about 26 m. This dike is 1.7 m wide and runs in a northeast direction (Fig. 9.8A,B). A significant portion of the section, about 14 m thick, is repeated from 27.75 m to 41.5 m (sub-unit III bis; in Fig. 9.25). This repetition is probably related to the presence of a major thrust-fault. This thrust is covered but its location can be inferred in the narrow area (less than 1 m wide) where the stratigraphic repetition begins. The section may contain two other smaller stratigraphic repetitions at 51 m and 66 m (VII bis and IV bis, respectively). There is some evidence of repetitions involving a single bed (at 47 m) as well as small scale thrusting within a bed (38 m; in Fig. 9.25).

The section has two calcareous units. The lower one lies approximately between 57 m and 59 m and the upper one between 81 m and 83.5 m (Fig. 9.25). Since these units appear to be slightly different, their occurrence confirms the presence of at least two calcareous members in the Providence Island Formation (Members I and III; 6.2). The upper one correlates with the upper calcareous member of the Isle La Motte section and probably with the base of the section of South Hero (Fig. 6.1). The lower calcareous member resembles the lower calcareous member of the Isle La Motte section (0.5-3.25 m; in Fig. 9.32) and, to a lesser extent, the calcareous members of the sections at Carver Falls and Boss Hogg's Quarry (Figs. 9.20 and 9.21). However, their correlation is proposed tentatively due to the structural complexity shown by the section at Town Farm Bay.

The section displays most of the lithofacies and structures that have been discussed in this study (Figs. 9.25, 2.16, 3.6, 7.2 and 7.3). Dedolostones have not been observed. However, in view of the fact that not all the calcareous dolostones or dolomitic limestones have been observed under the microscope, it is possible that some of these rocks may correspond to partially dedolomitized rocks.

Taken as a whole the dolostones above the lower calcareous member are more frequently laminated than those below it (Fig. 9.25). The post-Beekmantown unconformity is well displayed at about 91 m in the southern part of the outcrop (Figs. 6.6, 9.8A, and 9.25).

The late/post-diagenetic geological events that have affected the Providence Island Formation as well as the associated underlying and overlying deposits can be inferred from this outcrop. For details about the unconformity and these other events see chapters 6.5, 7.3, and 7.4..

9.2.9 Valcour, New York

This outcrop is located on a railroad cut where 2.25 m of section have been measured. The beds strike to the east-northeast and dip slightly to the north (Fig. 9.9). They contain well displayed planar stromatolites in association with small scours, intraclasts, fenestral cavities, and solution-collapse breccias (Fig. 9.26).

9.2.10 Providence Island, Vermont

The Formation takes its name from the dolostones that are exposed on the eastern shore of this island (1.2). However, it is thought that the section here is not the most representative of the formation (9.1). The beds strike generally to the north and dip gently to the east (Fig. 9.10). A normal fault can be observed at the base of the section and lies at the contact between the Providence

Island Formation and the underlying Fort Cassin Formation (Fig. 9.10). However, a few meters from the shore to the west and from the fault to the south, the Providence Island Formation can be observed to lie conformably on the Fort Cassin Formation. For more information about this contact see chapter 6.2. To the north of the eastern shore of the island a prominent thrust-fault is observed but this lies within the overlying Day Point Limestone (Fig. 9.10). The upper contact of the Providence Island Formation is covered but is believed to be fault-controlled because of the small thickness of the formation at this outcrop. Such a structural contact has been suggested by Fisher (1968). Therefore, it is thought that only the lowermost portion of the formation is represented here.

The section is characterized lithologically by the laminated character of most of the dolomitic lithofacies (2.4) (Fig. 3.7) and the abundance of dedolostones (2.9) (Fig. 2.17).

Other significant features include well-developed domal stromatolites at 3.75 m and 8.2 m (Figs. 9.27, 2.6, and 2.7), channel-fills (Figs. 3.7 and 3.9), , different types of carbonate- and chert-filled voids or nodules (Fig. 4.2), isolated small lenses as well as discontinuous beds of blue-black chert which occasionally show diapiric structures (Fig. 4.4), solution-collapse breccias (Fig. 4.5 and 4.6) and diagenetic joints (Fig. 4.6). For details on the description and interpretation of these structures see chapters 2.4, 4.2, 4.3, and 4.5, respectively.

9.2.11 South Hero, Vermont

The outcrop is in an area about 500 m x 250 m where the Providence Island Formation and the overlying Day Point Limestone are discontinuously exposed. The beds strike to the west-northwest and dip gently to the north (Fig. 9.11). The most significant feature of this outcrop is probably the presence of a 87 m horizontal offset of the beds of both formations along a 25 m wide belt where rock exposures are missing (Fig. 9.11). It is thought that this offset results from the presence of a fault. Its orientation (N 22^0 E) and dip (78^0 E) has been inferred from the existence of small fractures whose orientation is consistent to that shown by the belt (Fig. 9.11). The characteristics of the topography, the sense of the offset as well as of the strike and dip of the beds suggest the presence of an unexposed thrust-fault where the upper block moved to the west-northwest along the belt. This interpretation is consistent with the common presence of equivalent faults in other outcrops, such as Town Farm Bay, Vermont (9.2.8) and with the occurrence of a thrust-fault mapped by Erwin (1957) at this exact locality. However, the possibility that this fault may represent a sinistral or a combined sinistral-thrust fault is not discarded. In any case, this structure presumably developed during the Taconic Orogeny (7.4).

The base of the section is calcareous (Fig. 9.28) and probably represents the top part of the upper calcareous member of the formation (Member III) (Fig. 6.1). The outcrop contains the post-Beekmantown unconformity, although it is covered. The basal impure quartz-arenites of the Day Point Limestone found at Isle La Motte (9.2.14) have not been observed here. However, the almost matrix-free quartz-arenites found at this section on South Hero (6.5 m - 7.5 m; in Fig. 9.28) are similar to those found at the Town Farm Bay and Isle La Motte sections at about 91.25 m and 27.5 m, respectively (Figs. 9.25 and 9.32). The presence of accesory ferroan dolomite and phosphatic brachiopod fragments (probably linguloids) is characteristic of these arenites.

9.2.12 Saranac River, New York

The section is only 6 m thick but is exceptionally well exposed just west of the Route 87 bridge in an old sluiceway on the north side of the river (Fig. 9.12). The strata strike to the northwest and dip slightly to the northeast. Significant features include the presence of burrowed and mudcracked flat-lying stromatolites (3.25 m and 4 m; in Fig. 9.29) (Fig. 2.4C,D), channel-fill deposits (3.7 m), and calcite as well as calcite-dolomite nodules of variable size which occasionally contain gypsum and/or anhydrite crystals (Figs. 2.4B, 4.1, and 4.3). The latter structures may indicate that the section represents a portion of the upper part of the formation (Member IV; 6.2) (4.1). Irregular and large polygonal mudcracks are features that only have been observed at this section at 2.75 m and 3.5 m, respectively (Figs. 3.2 and 3.4). For details on all these structures see chapters 2.4, 3, and 4.

9.2.13 Beekmantown, New York

Two sections have been measured at this outcrop: A (east) and B (west) (Figs. 9.30 and 9.31). Based on the structural characteristics of the outcrop it seems likely that section B overlies section A (Fig. 9.13). The only significant feature of this outcrop is the presence of a normal fault that affects section A. This fault runs N 60^0 E, dips 65^0 E and shows a vertical throw of 1.28 m (Fig. 9.13). The beds strike to the northeast and dip gently to the northwest.

9.2.14 Isle La Motte, Vermont

As noted above, this section is considered to be the most representative one of the Providence Island Formation since it is more than 25 m thick, undeformed, continuous, and well exposed. The outcrop is located at the southernmost shore of the island and, occasionally, is only accessible by boat (Fig. 9.14). The strata generally strike to the northeast and dip slightly to the northwest. It is affected by at least one major bedding-plane fault that is probably a thrust-fault but which does not break the continuity of the strata. The trend and plunge of the associated slickensides are N 129^0 E and 3^0 W, respectively. The "steps" shown by them suggest a displacement of the upper block to the west-northwest which is consistent with the inferred tectonic movements in southern areas (e.g. South Hero, Vermont, and Town Farm Bay, Vermont). A prominent normal fault is observed at about 25 m, near the top of the formation (Figs. 9.14 and 9.32). Its trend and dip is N-S and 52-81^0 W, respectively, and the vertical throw is about 50 cm. The rocks frequently contain small fractures that commonly are sub-vertical and have a variable orientation. Their throw is very small or absent.

The section contains most of the described lithofacies and structures (Figs. 2.1, 2.5, 2.10A,B, 2.14, 2.15, 3.1, 3.5, and 3.8). Dedolostones have not been observed and carbonate as well as chert nodules or lenses are very rare. However, dedolostones may exist based on the same reasons given for the Town Farm Bay section (9.2.8). As has already been stated, the section shows the upper calcareous member (Member III; 6.2) of the formation (18.5-22.3 m) as well as the laminated facies of the ovelying dolomitic member (Member IV) (Fig. 9.32). Near the base, between 0.5 m and 3.3 m, the section presents mixed calcareous-dolomitic deposits. It seems likely that this portion represents the other underlying calcareous member of the formation (Member I). The post-Beekmantown unconformity is well exposed at about 25.5 m (Figs. 9.14 and 9.32). Its characteristics as well as its implications are discussed in chapters 6.5 and

7.3.

The correlation of this section with other sections of the outcrop belt is presented in Figure 6.1.

9.2.15 Napierville, Quebec

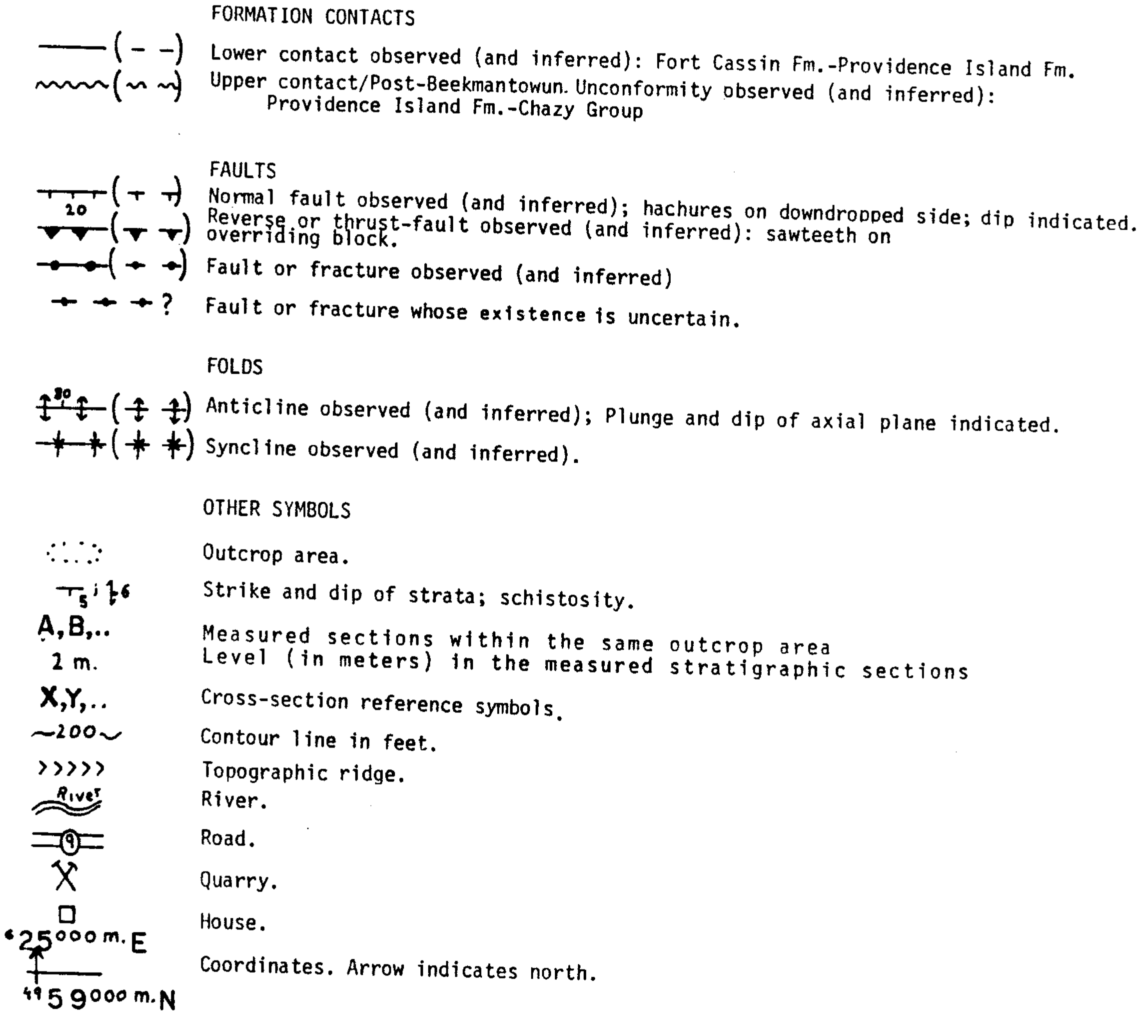
This outcrop is poorly exposed at the bank of a small stream (Fig. 9.15). The mesured section is only 1 m thick (Fig. 9.33) and is thought that it corresponds to the Providence Island Formation since similar deposits occur in southern sections of the formation. This interpretation is also supported on view of the fact that bedding is sub-horizontal (Fig. 9.15) and beds that seem to belong to the overlying Day Point Limestone have been observed only 4 km to the northeast from this outcrop.

9.3 Index maps

9.3.1 General statement

The index maps presented here show the exact location of most of the outcrops of the Providence Island Formation. These localities have been plotted in Figure 1.1 in a more general context. Also, these maps show the important geological and geomorphological features of the outcrop. Geological cross-sections are presented with some maps. When an outcrop contain two measured sections, the exact location of each section is shown in the corresponding map.

9.3.2 Maps



FORMATION CONTACTS

Lower contact observed (and inferred): Fort Cassin Fm.-Providence Island Fm.

Upper contact/Post-Beekmantowun. Unconformity observed (and inferred): Providence Island Fm.-Chazy Group

FAULTS

Normal fault observed (and inferred); hachures on downdropped side; dip indicated.

Reverse or thrust-fault observed (and inferred): sawteeth on overriding block.

Fault or fracture observed (and inferred)

Fault or fracture whose existence is uncertain.

FOLDS

Anticline observed (and inferred); Plunge and dip of axial plane indicated.

Syncline observed (and inferred).

OTHER SYMBOLS

Outcrop area.

Strike and dip of strata; schistosity.

Measured sections within the same outcrop area

Level (in meters) in the measured stratigraphic sections

Cross-section reference symbols.

Contour line in feet.

Topographic ridge.

River.

Road.

Quarry.

House.

Coordinates. Arrow indicates north.

Fig. 9.1.- Legend to index maps

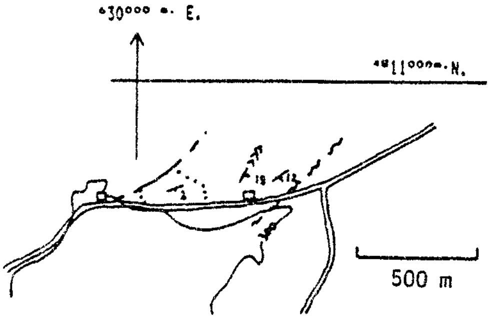


Fig. 9.2.- Deweys Bridge Road, Comstock, New York.

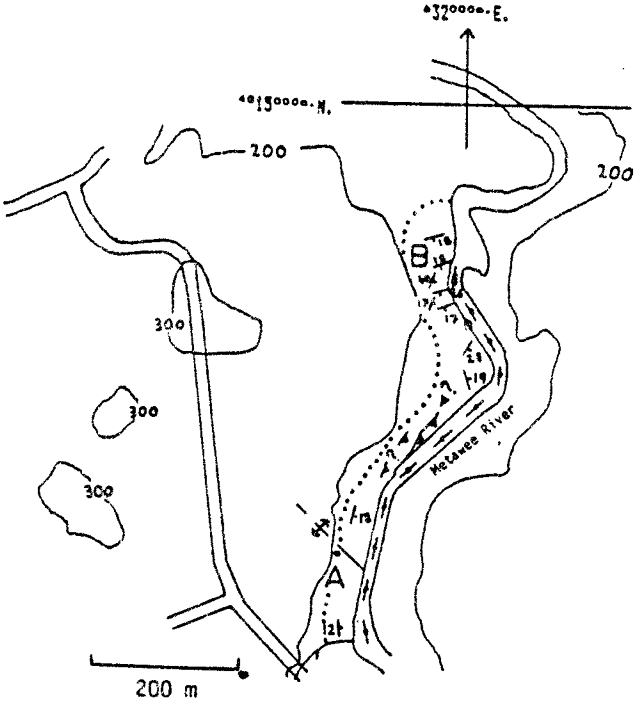


Fig. 9.3.- Granville Public Fishing Site, New York.

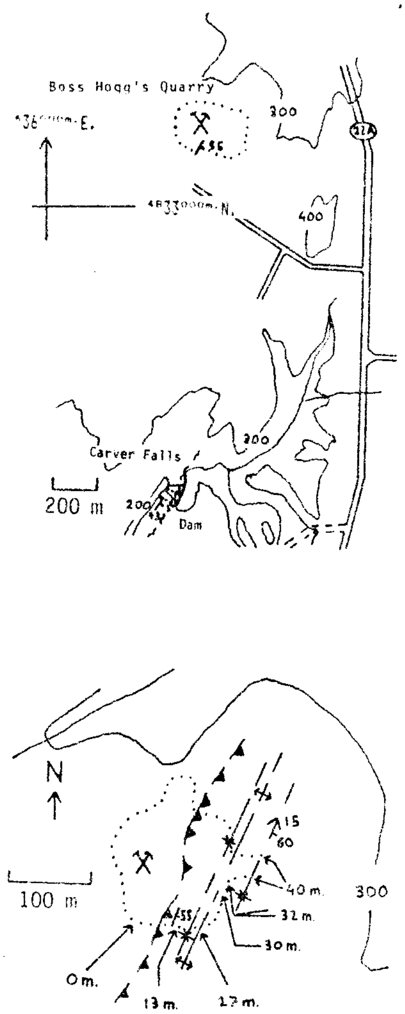


Fig. 9.4.- A) Carver Falls and Boss Hogg's Quarry, West Haven, Vermont. B) Boss Hogg's Quarry (enlarged).

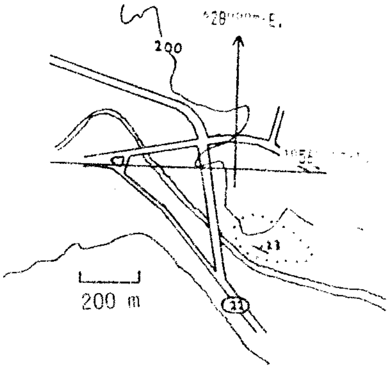


Fig. 9.5.- Ticonderoga, New York.

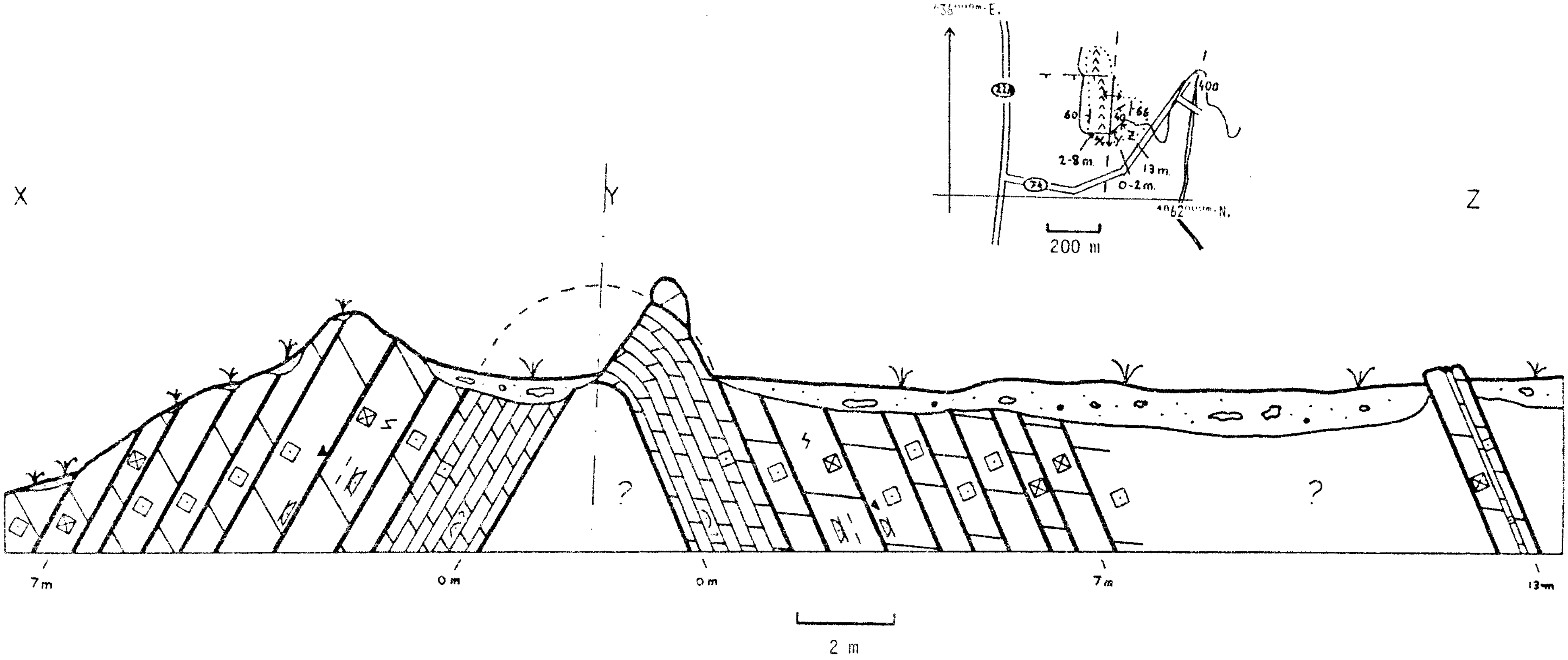


Fig. 9.6.- A) Shoreham, Vermont. B) Cross-section at this outcrop.

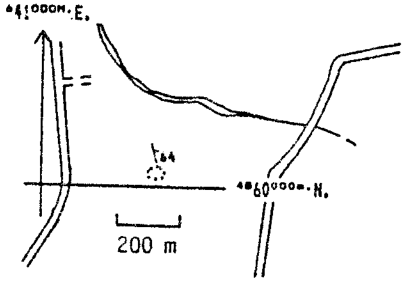


Fig. 9.7.- East Shoreham, Vermont.

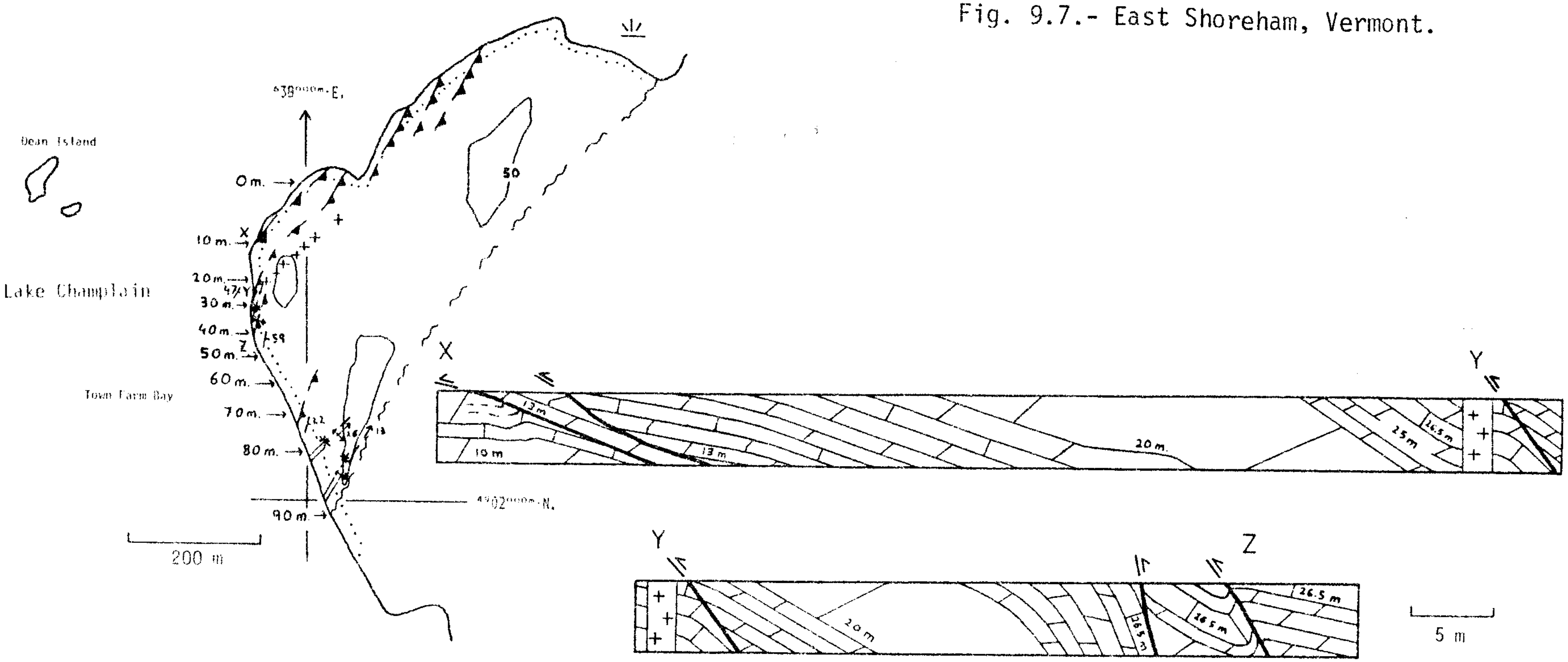


Fig. 9.8.- A) Town Farm Bay, North Ferrisburg, Vermont. B) Cross-section at this outcrop.

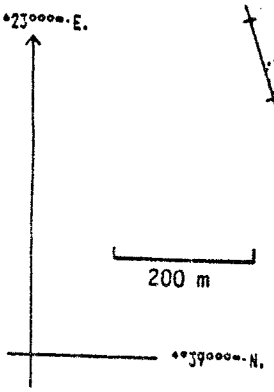


Fig. 9.9.-

Valcour, New York.

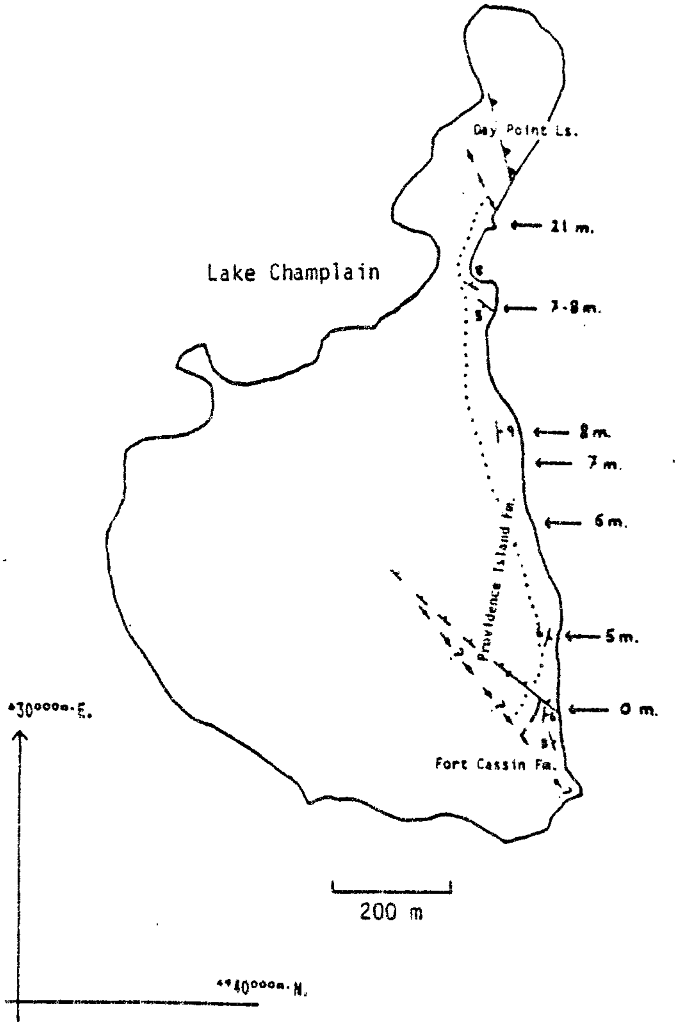


Fig. 9.10.-

Providence Island, Vermont.

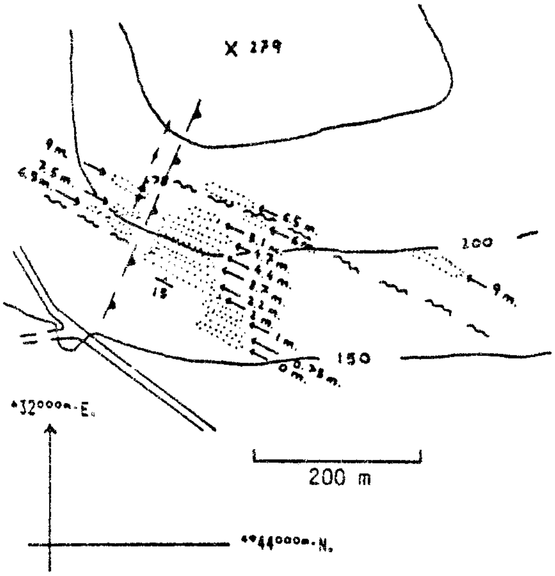


Fig. 9.11.-

South Hero, Vermont.

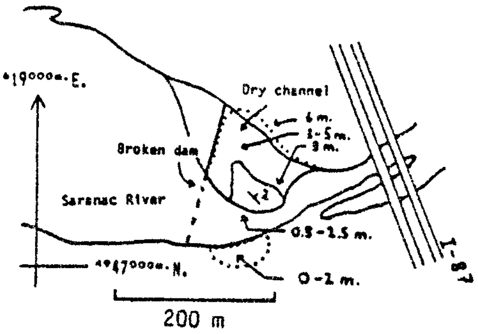


Fig. 9.12.- Saranac River, Plattsburgh, New York.

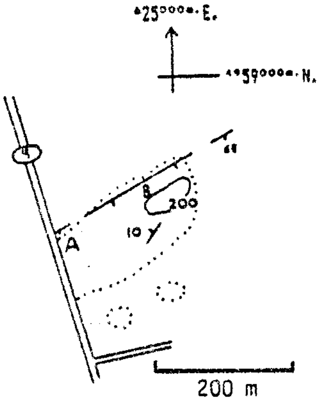


Fig. 9.13.- Beekmantown, New York.

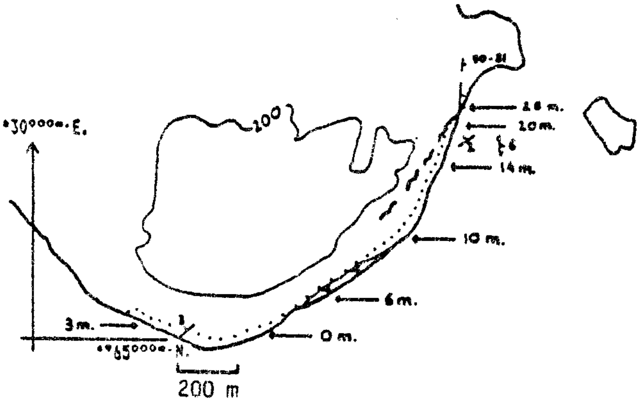


Fig. 9.14.-

Isle La Motte, Vermont.

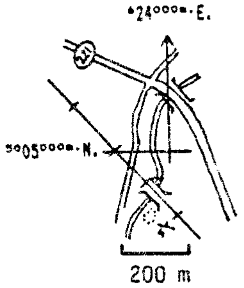


Fig. 9.15.-

Napierville, Quebec.

9.4 Graphic representation of the measured sections

9.4.1 Explanation of general format

The measured sections represented here are listed under the same name of the outcrop where they are located. If two sections have been measured within the same outcrop, each one is designated by a letter that represents a locality within the outcrop (e.g. locality A). Such localities are shown in the outcrop index maps.

Particular rock features(e.g. chert nodules) are always represented in the sections at the same horizontal distance from the vertical scale. This distance is shown in the "key" section (Fig. 9.16). For example, chert nodules are represented in the internal fourth sub-column at a location about 2 cm to the left from the vertical scale. Therefore, if the reader wants to check for chert nodules on a particular section, he has to look along a line that is parallel and located 2 cm to the right from the vertical scale

Sometimes, features that are only characteristic of a particular section are not noted on the "key" column but on that section with an explanation.

9.4.2 Sections:

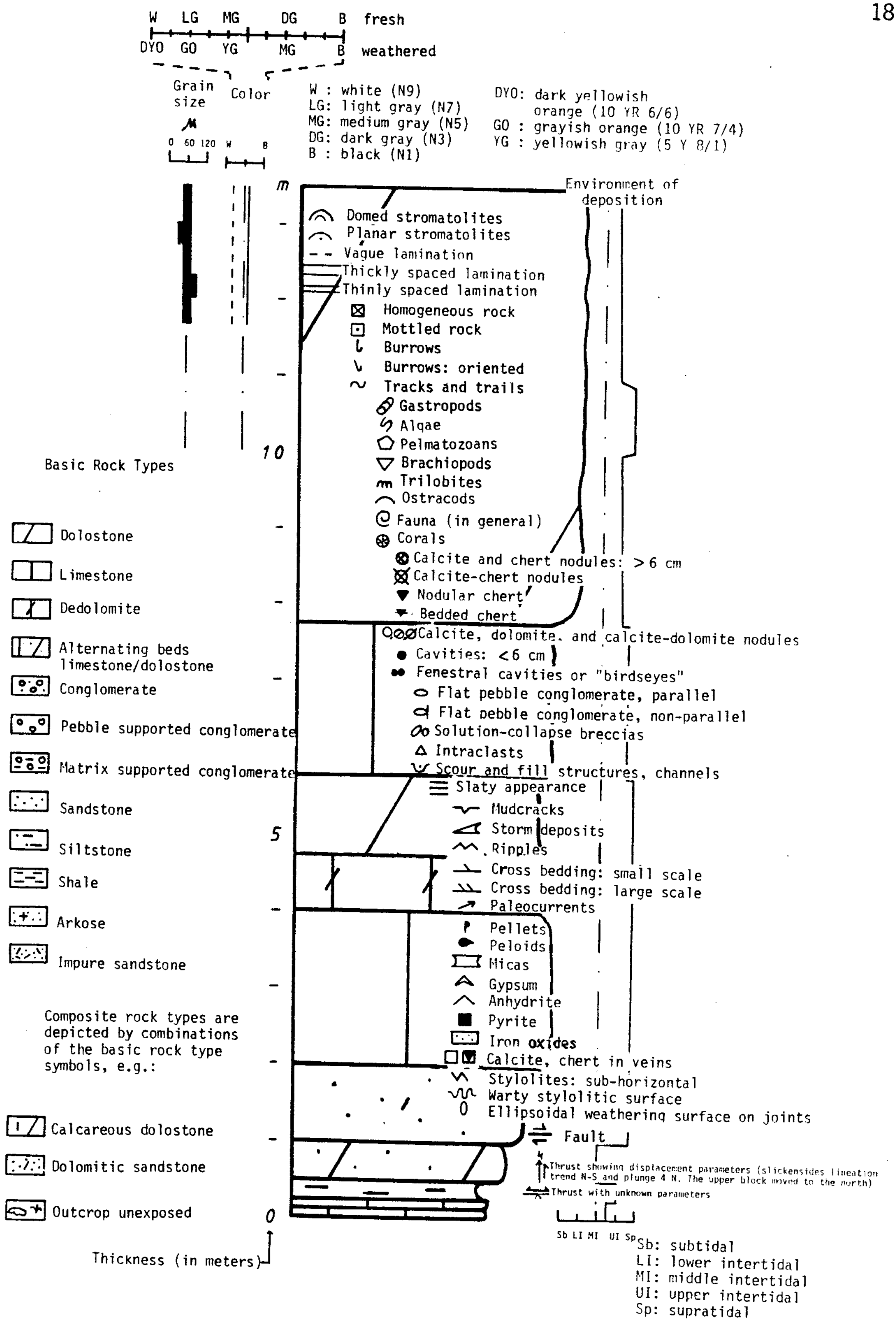


Fig. 9.16.- Key to measured sections illustrating lithology, particles, structures (sedimentary, diagenetic, and tectonic) and accesory logs.

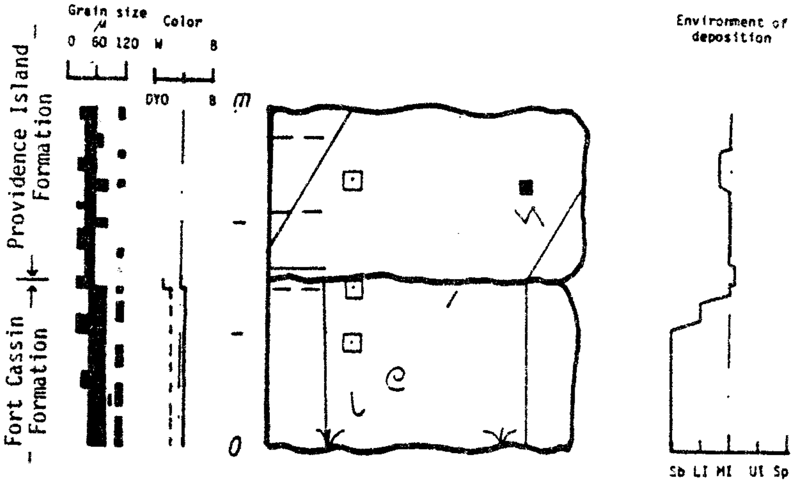


Fig. 9.17.- Deweys Bridge Road , Comstock, New York.

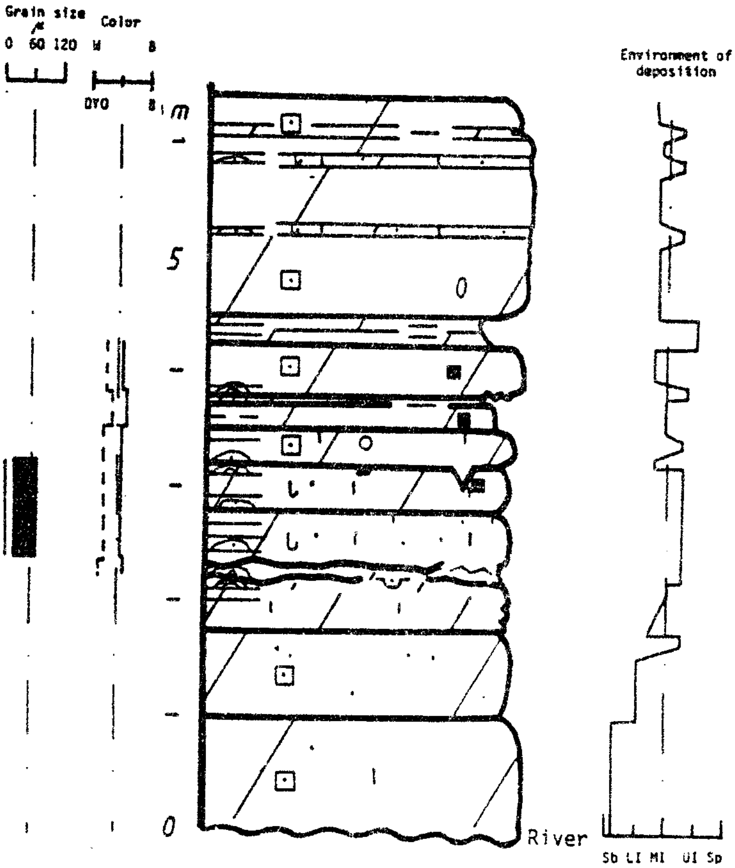


Fig. 9.18.- Granville Public Fishing Site (locality A), New York.

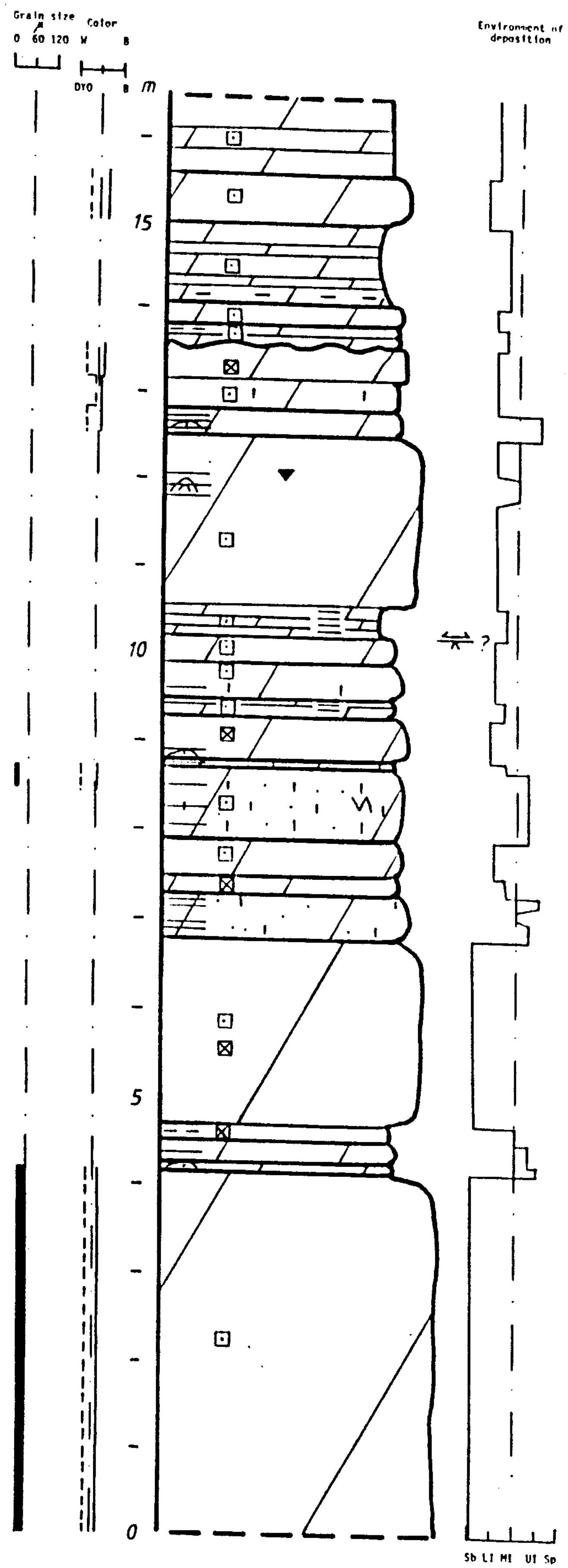


Fig. 9.19 (I).- Granville Public Fishing Site (locality B), New York.

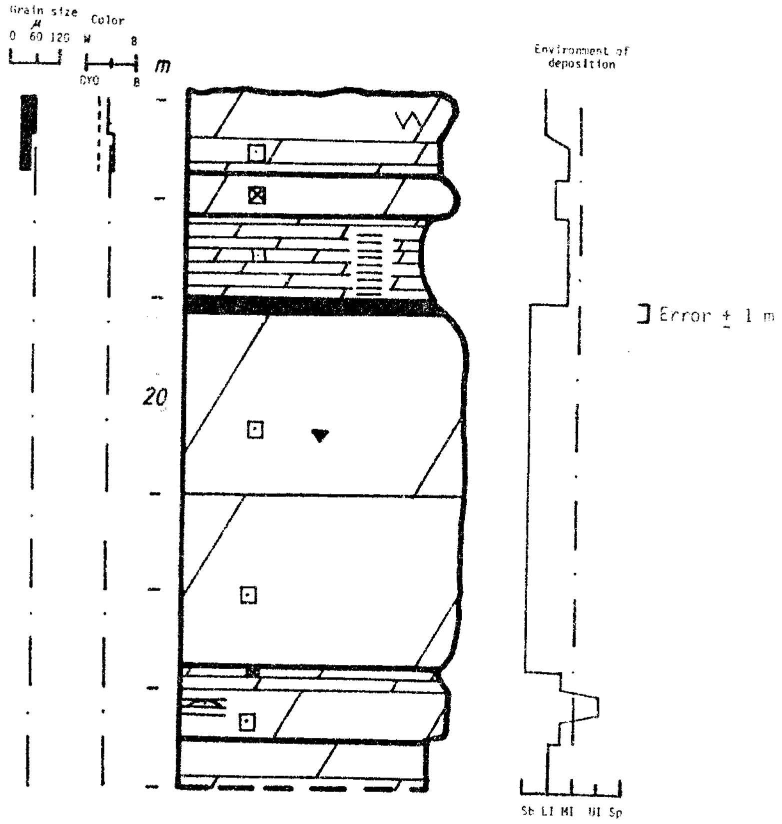


Fig. 9.19 (II).- Granville Public Fishing Site (locality B), New York.

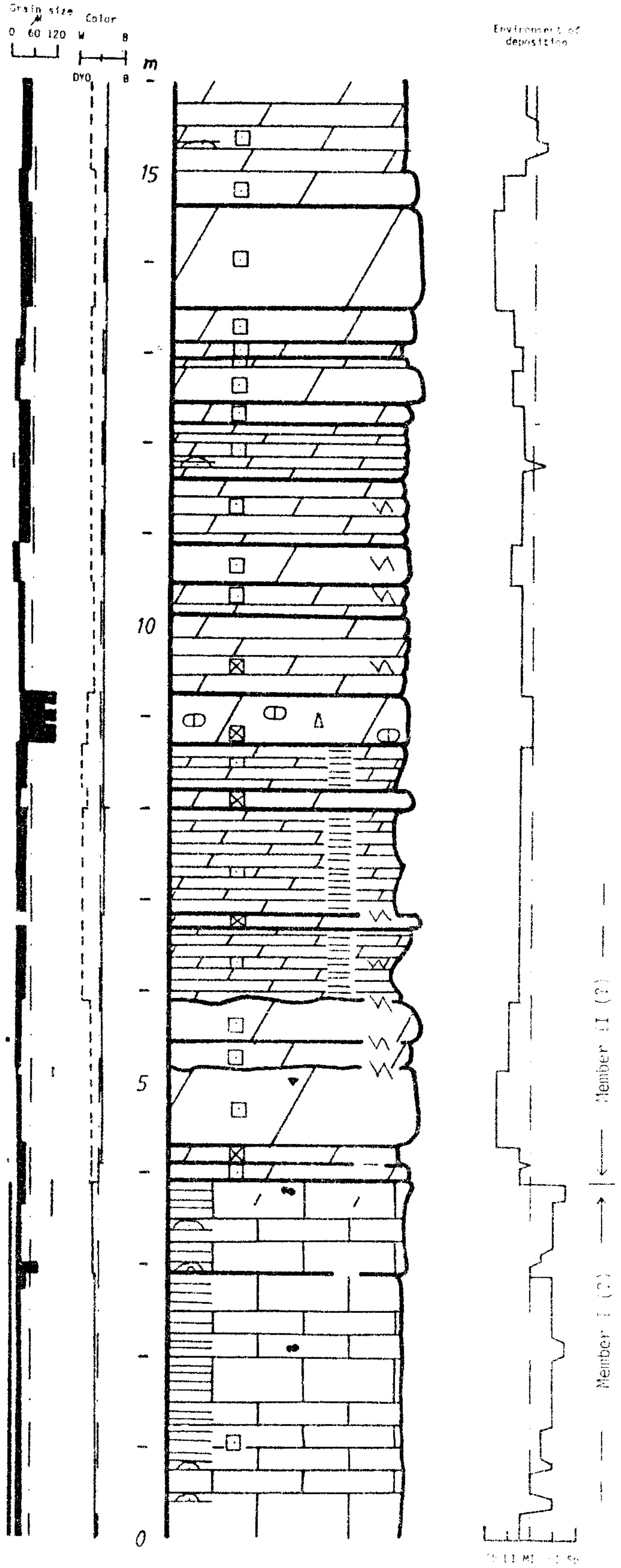


Fig. 9.20 (I).- Carver Falls, West Haven, Vermont.

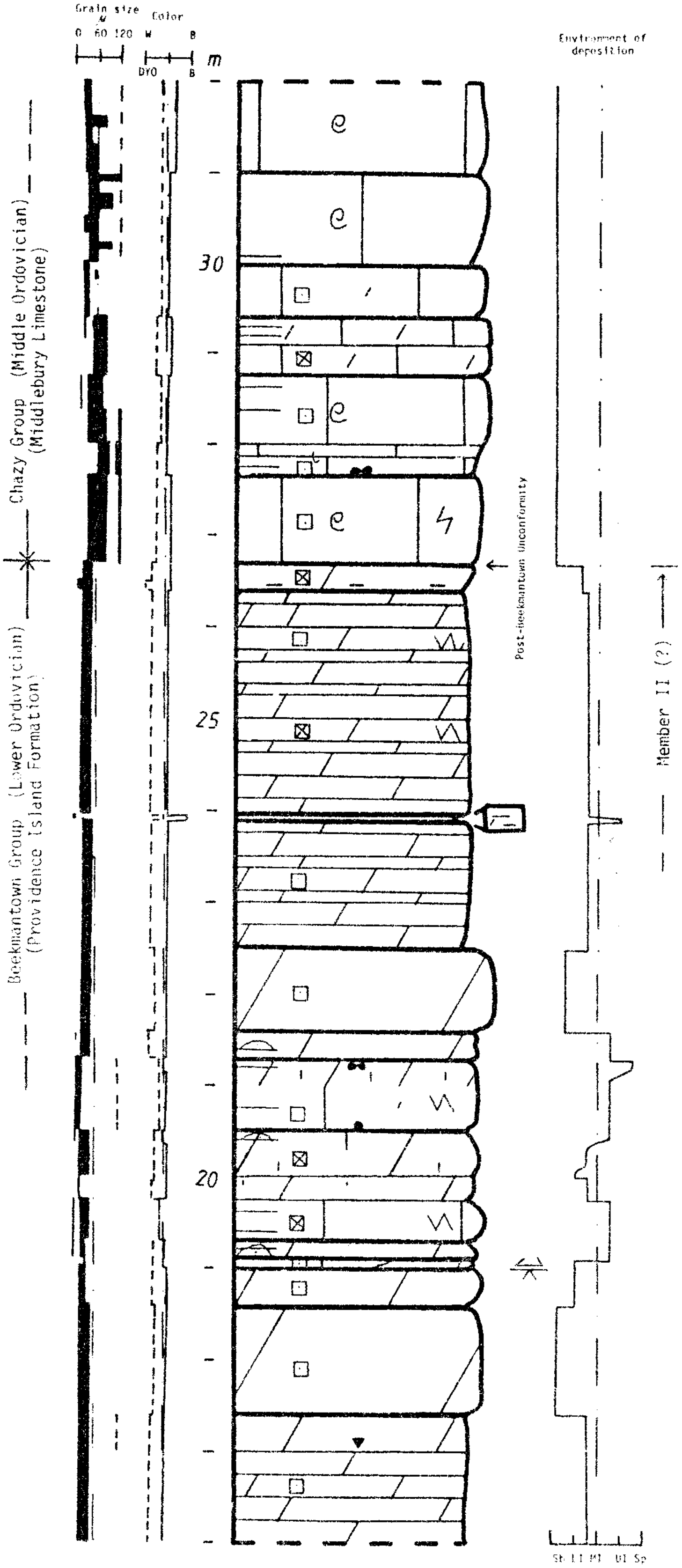


Fig. 9.20 (II).- Carver Falls, West Haven, Vermont.

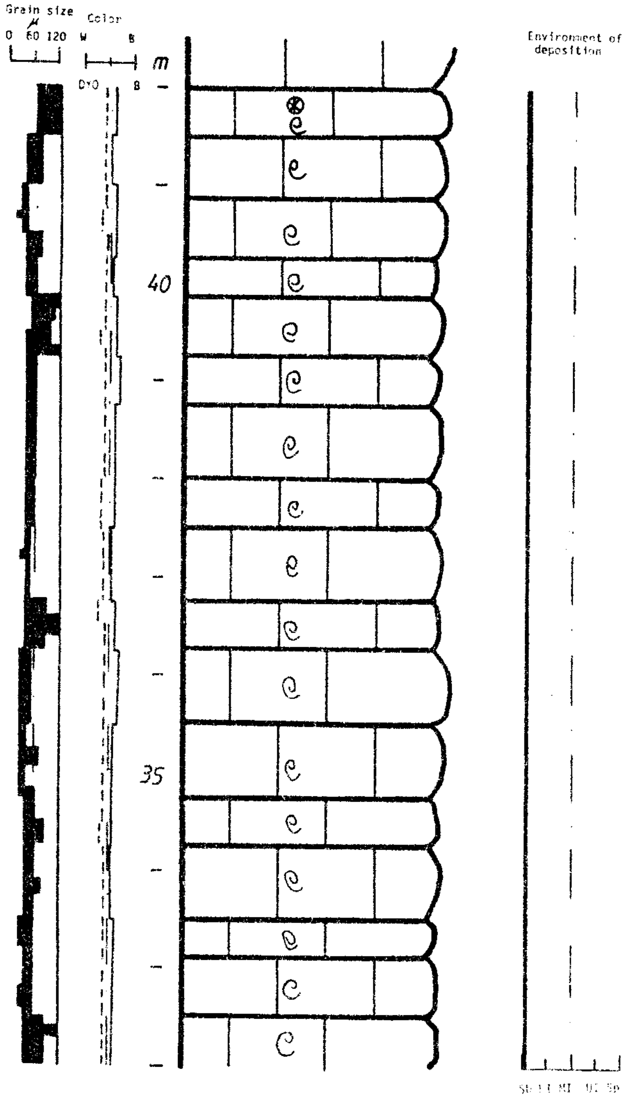


Fig. 9.20 (III).- Carver Falls, West Haven, Vermont.

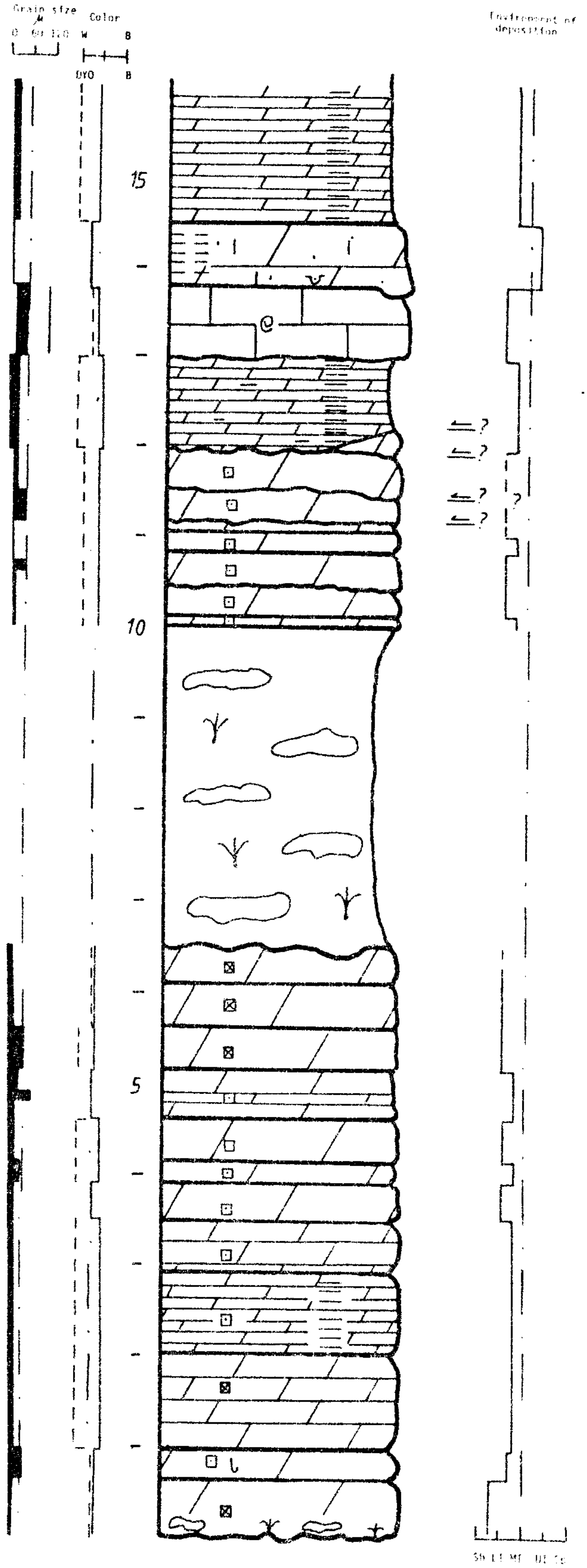


Fig. 9.21 (I).- Boss Hogg's Quarry, West Haven, Vermont.

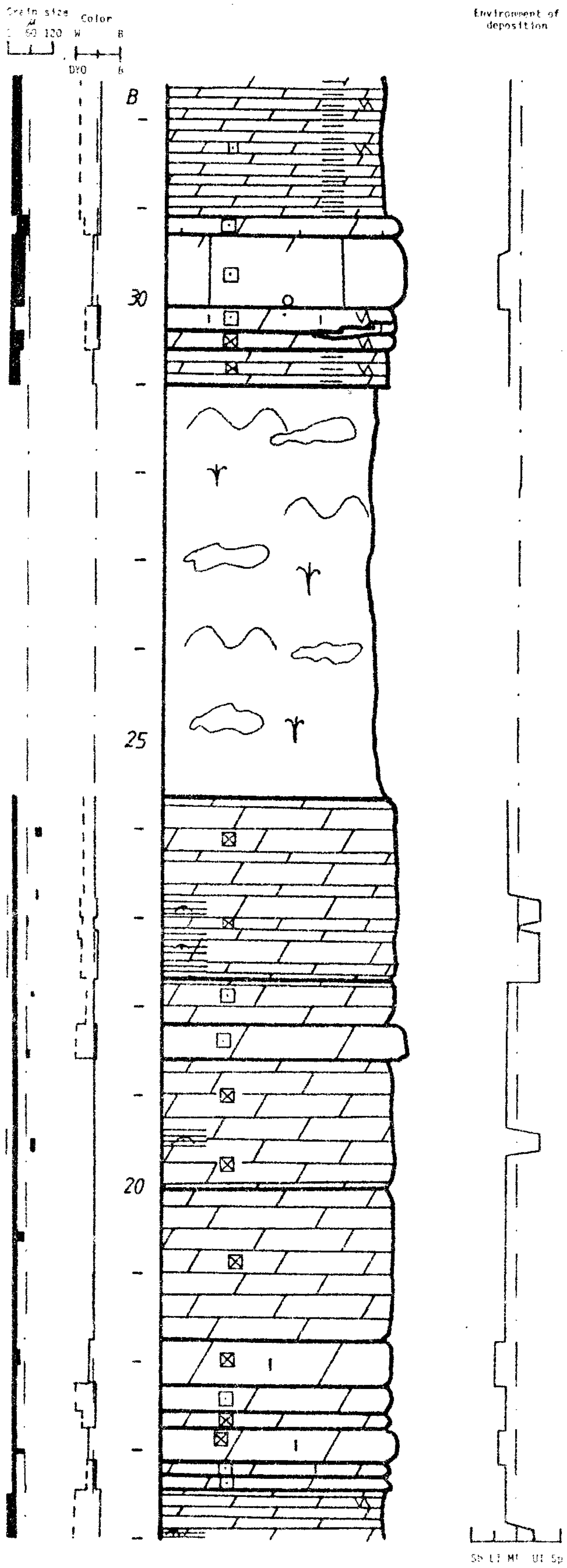


Fig. 9.21 (II).- Boss Hogg's Quarry, West Haven, Vermont.

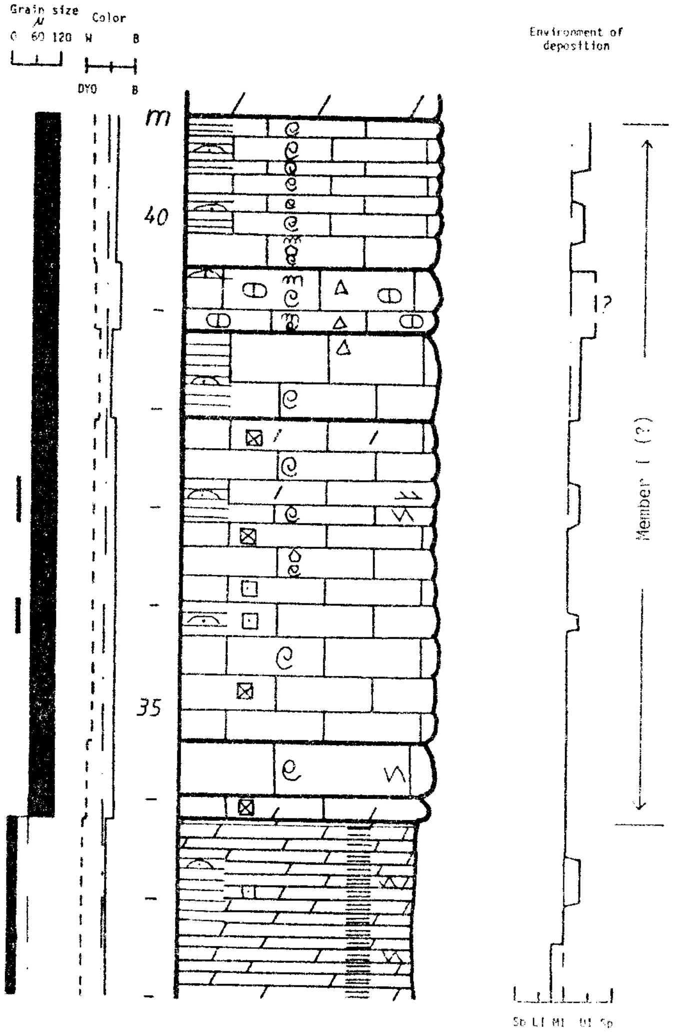


Fig. 9.21 (III).- Boss Hogg's Quarry, West Haven, Vermont.

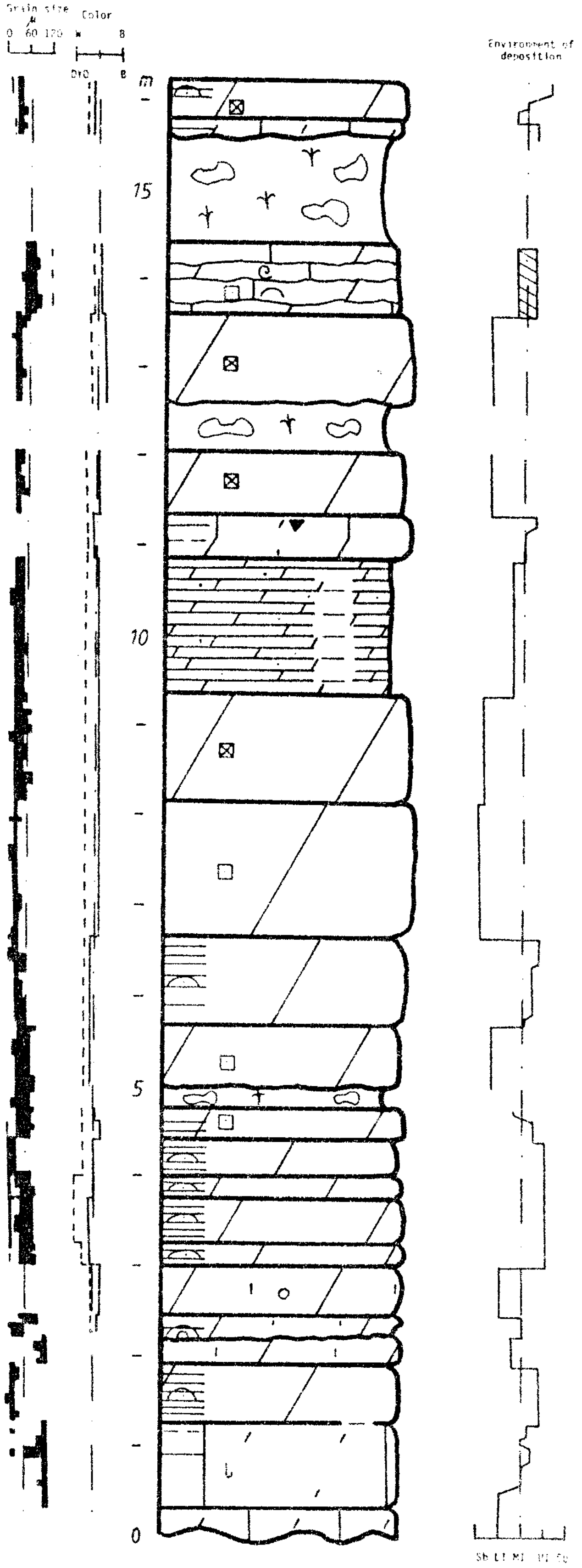


Fig. 9.22 (I).- Ticonderoga, New York.

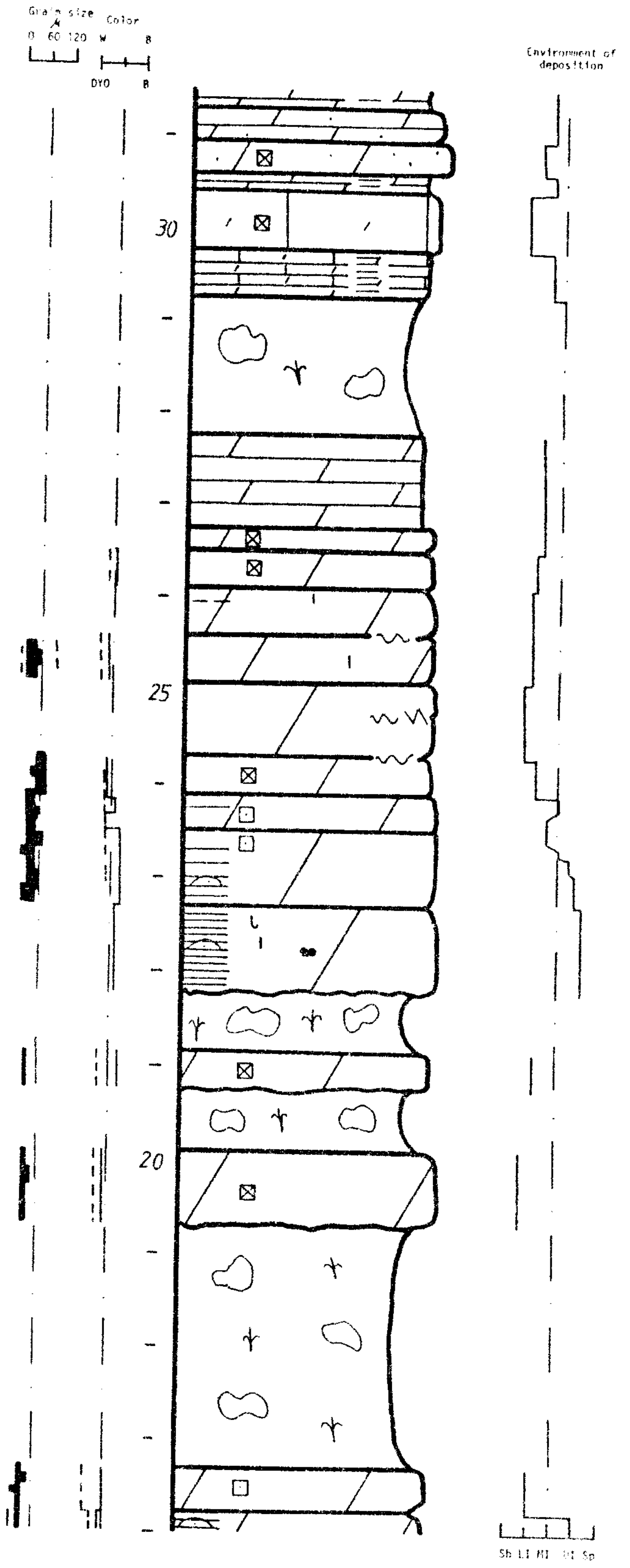


Fig. 9.22 (II).- Ticonderoga, New York.

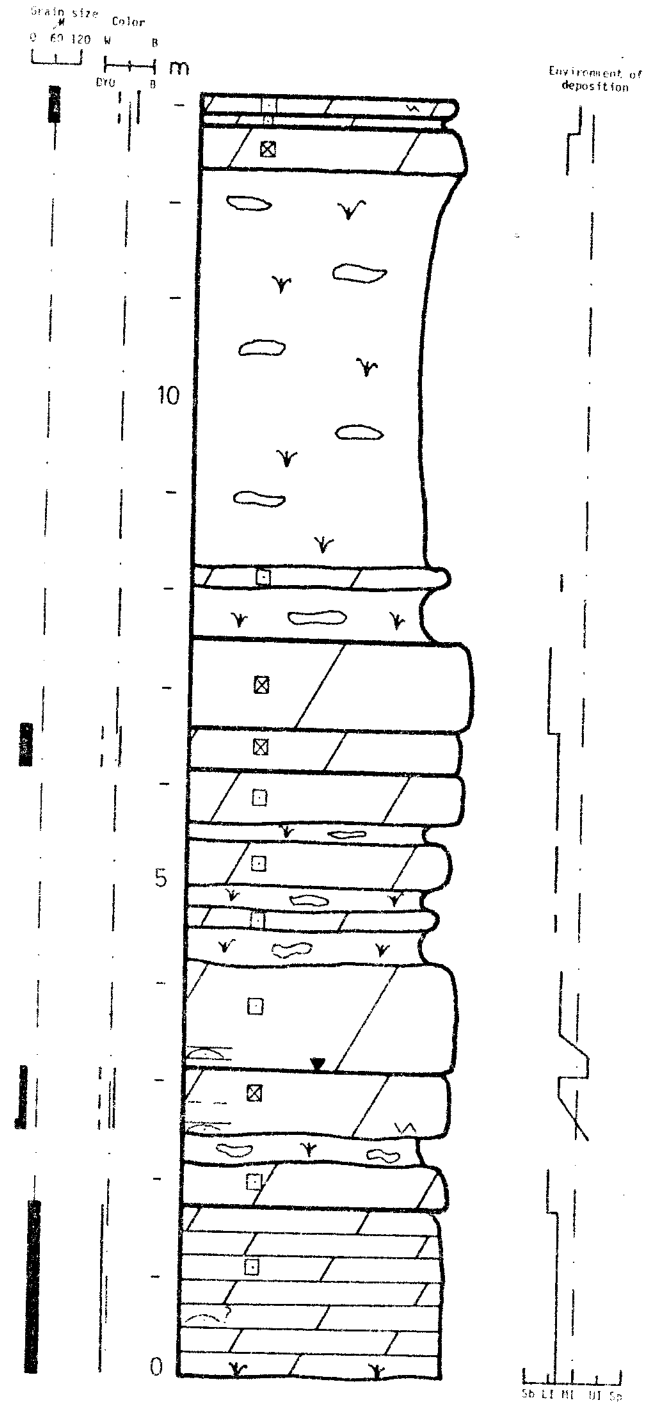


Fig. 9.23.- Shoreham, Vermont.

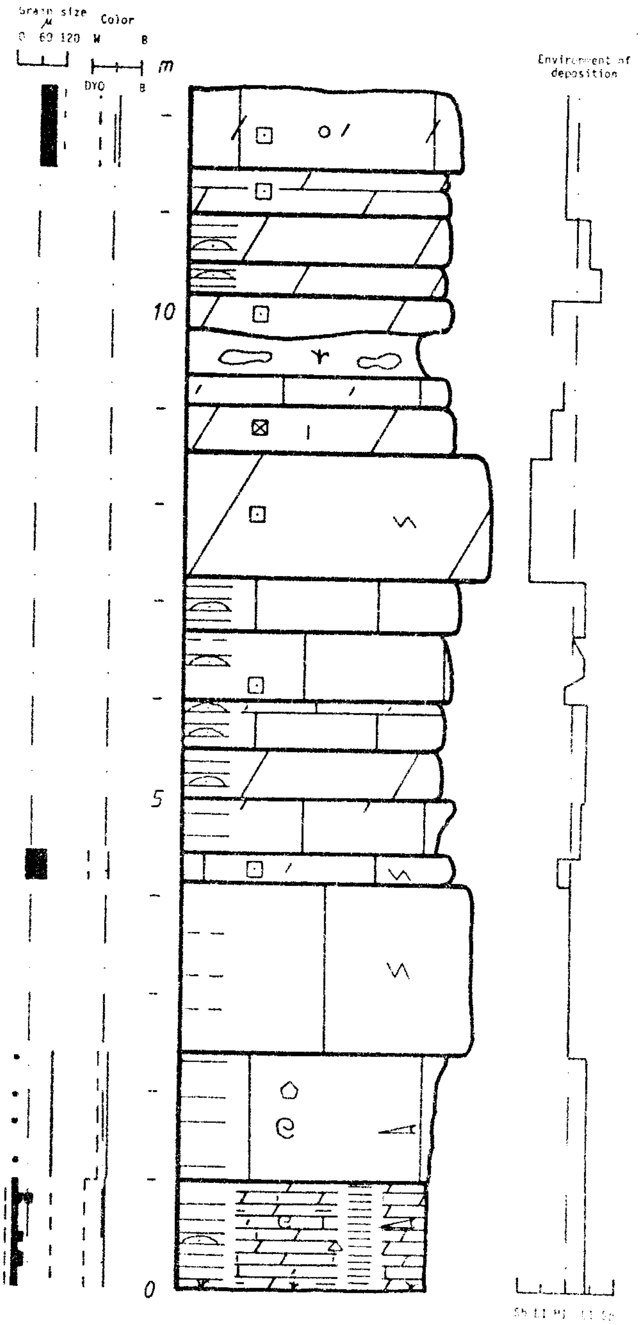


Fig. 9.24.- East Shoreham, Vermont.

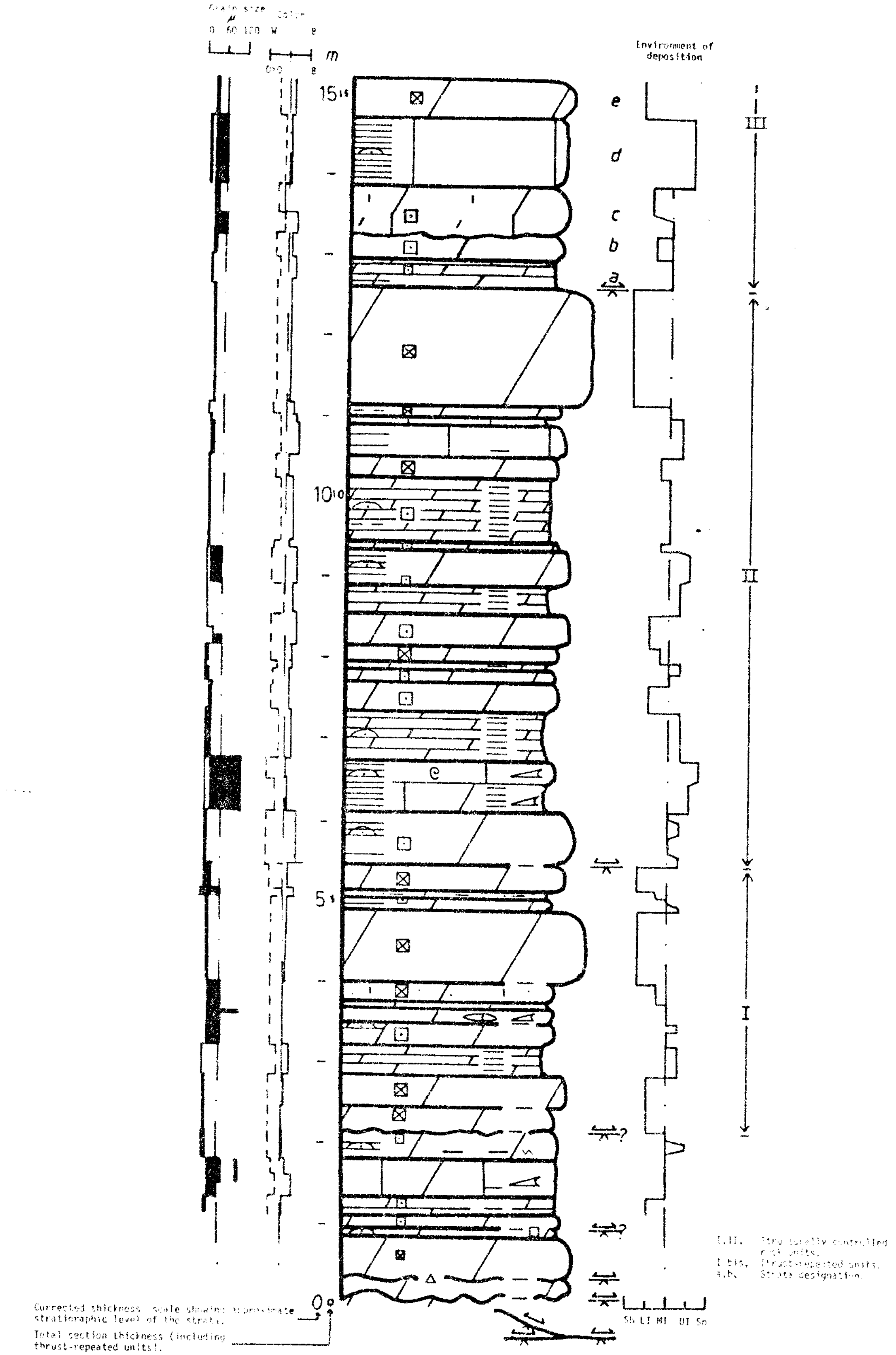


Fig. 9.25 (I).- Town Farm Bay, North Ferrisburg, Vermont.

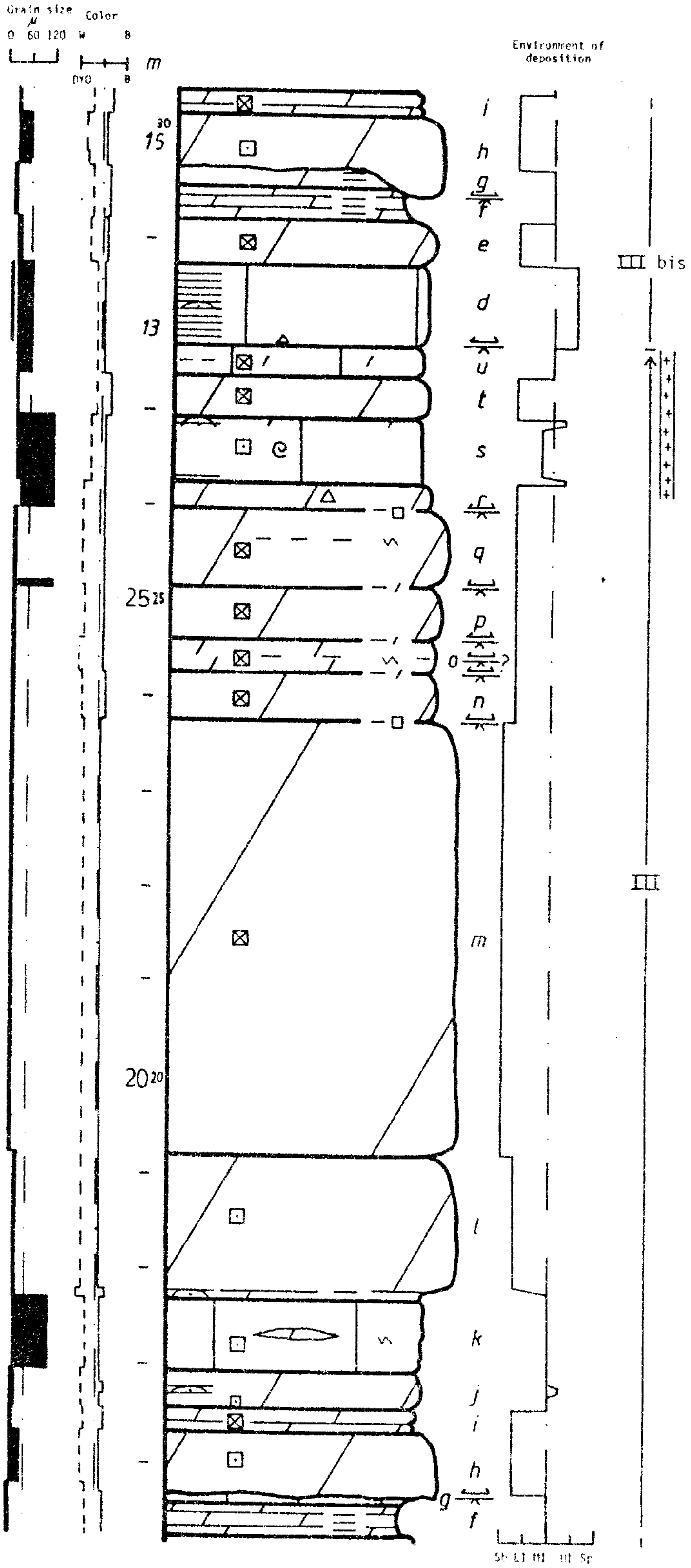


Fig. 9.25 (II).- Town Farm Bay, North Ferrisburg, Vermont.

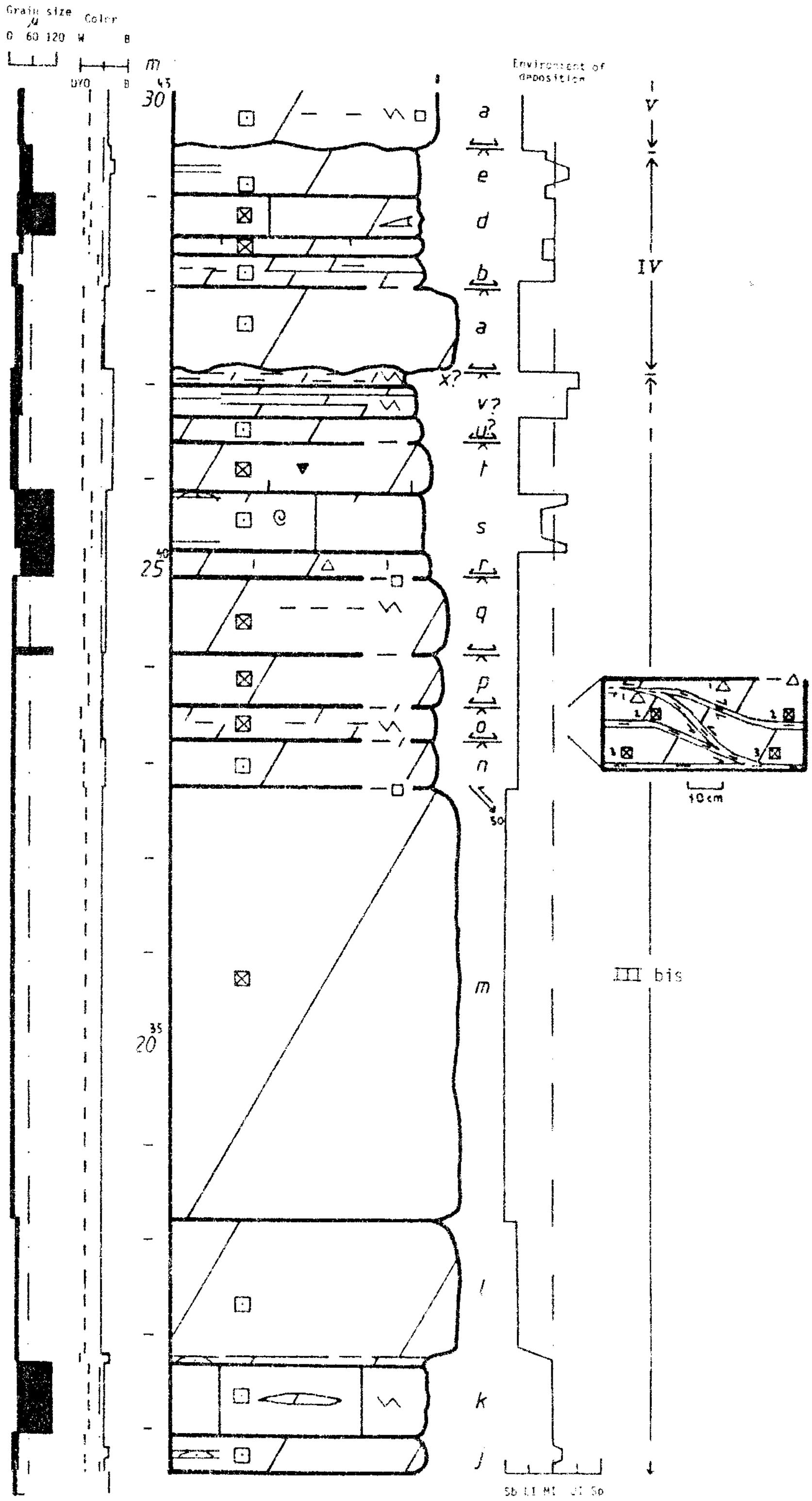


Fig. 9.25 (III).- Town Farm Bay, North Ferrisburg, Vermont.

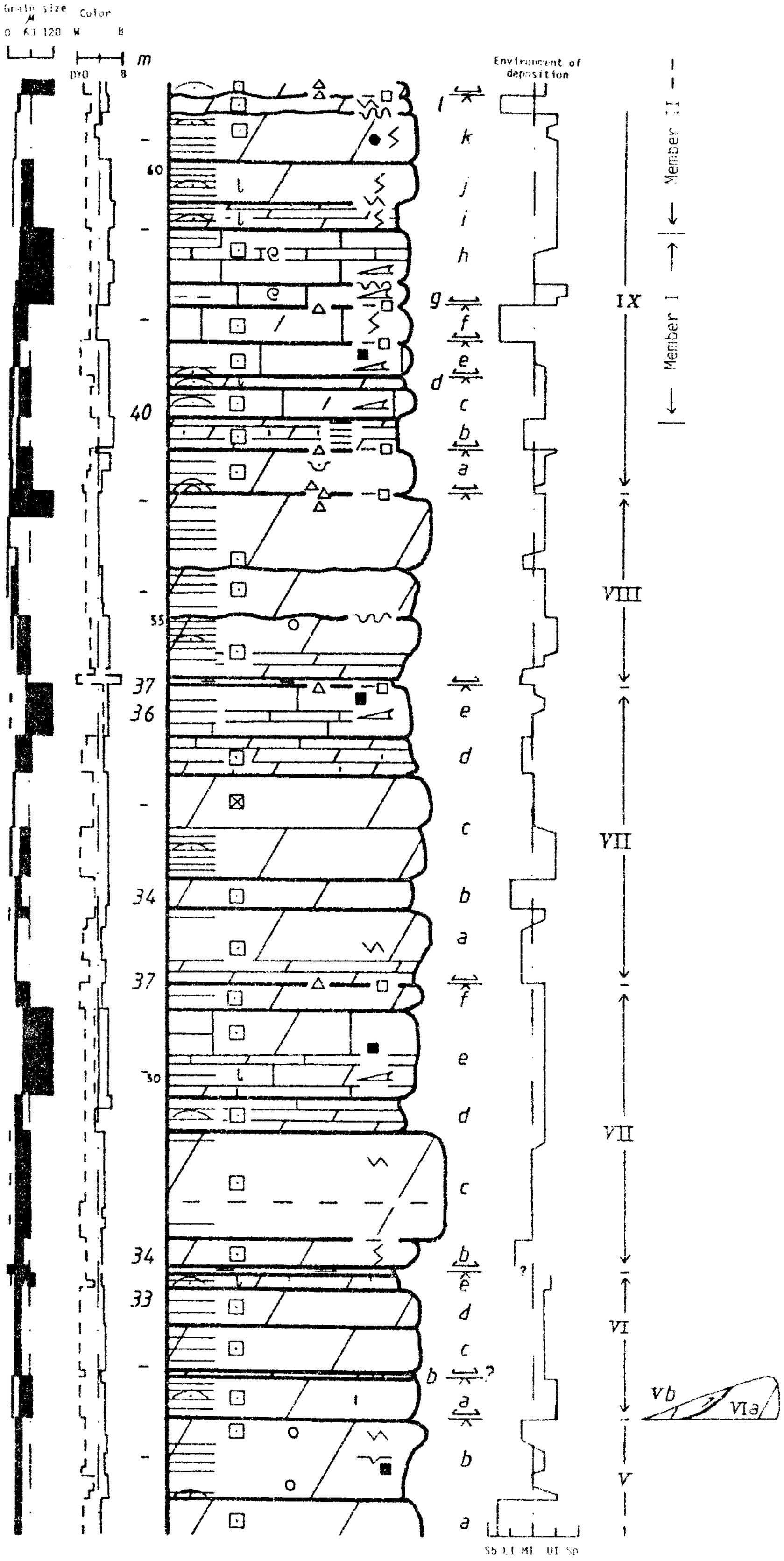


Fig. 9.25 (IV).- Town Farm Bay, North Ferrisburg, Vermont.

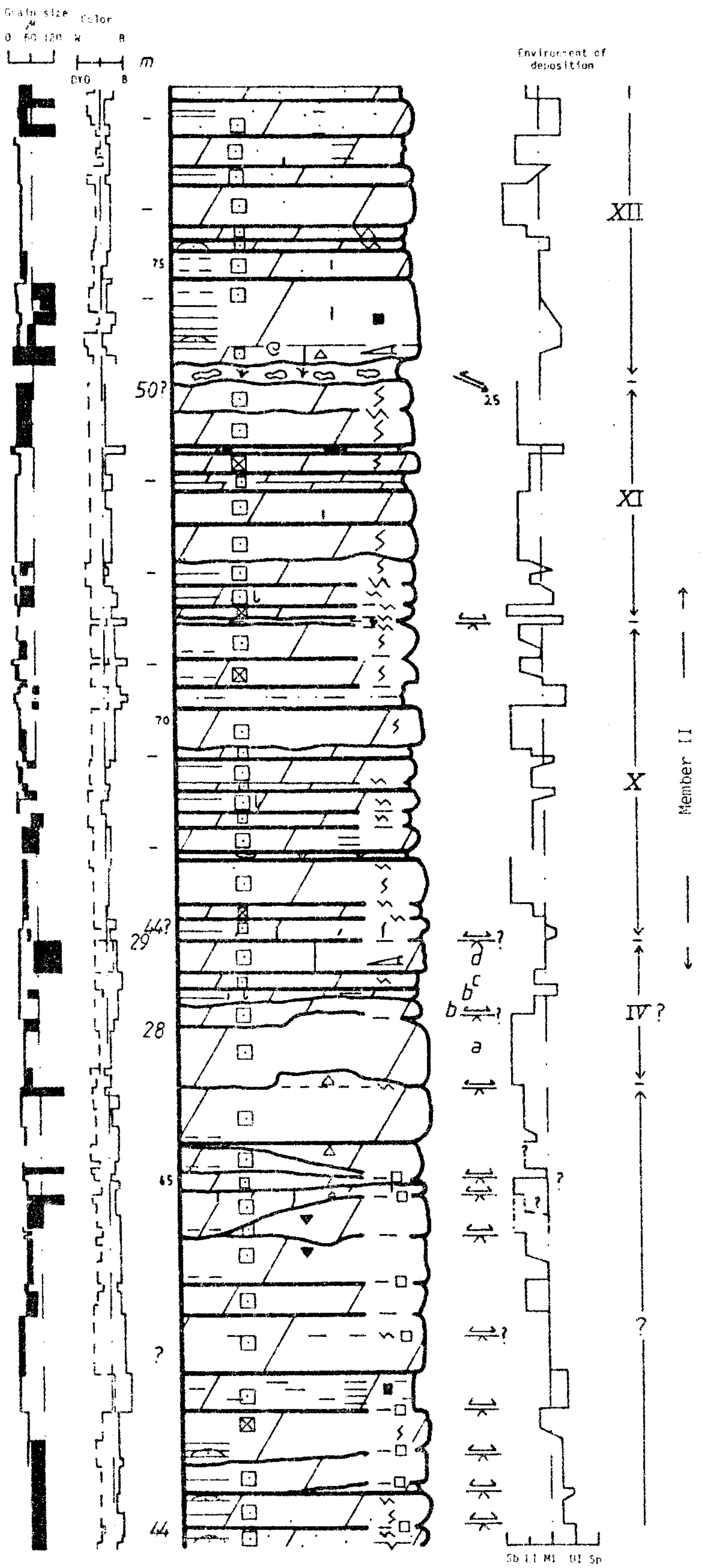


Fig. 9.25 (V).- Town Farm Bay, North Ferrisburg, Vermont.

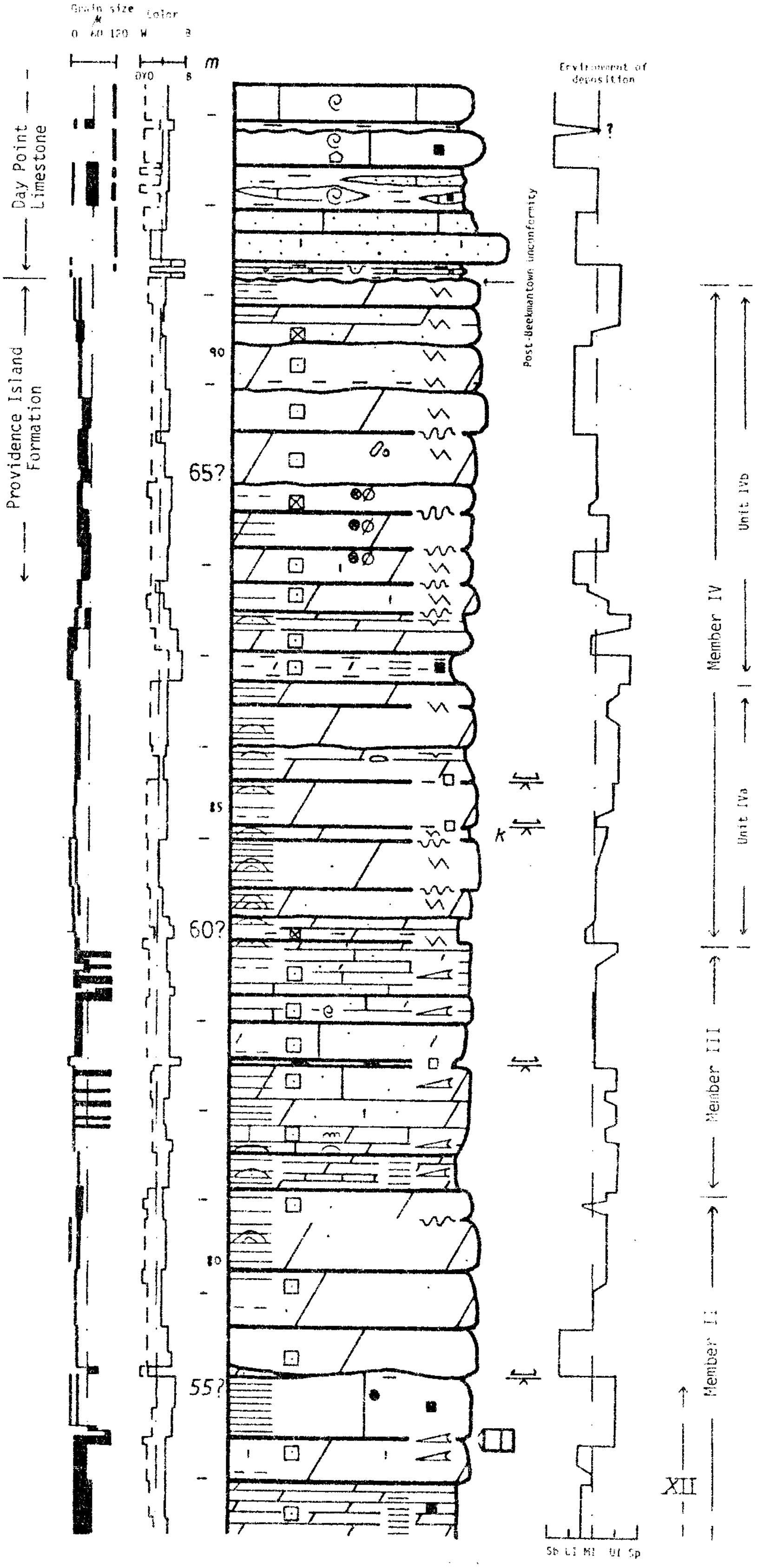


Fig. 9.25 (VI).- Town Farm Bay, North Ferrisburg, Vermont.

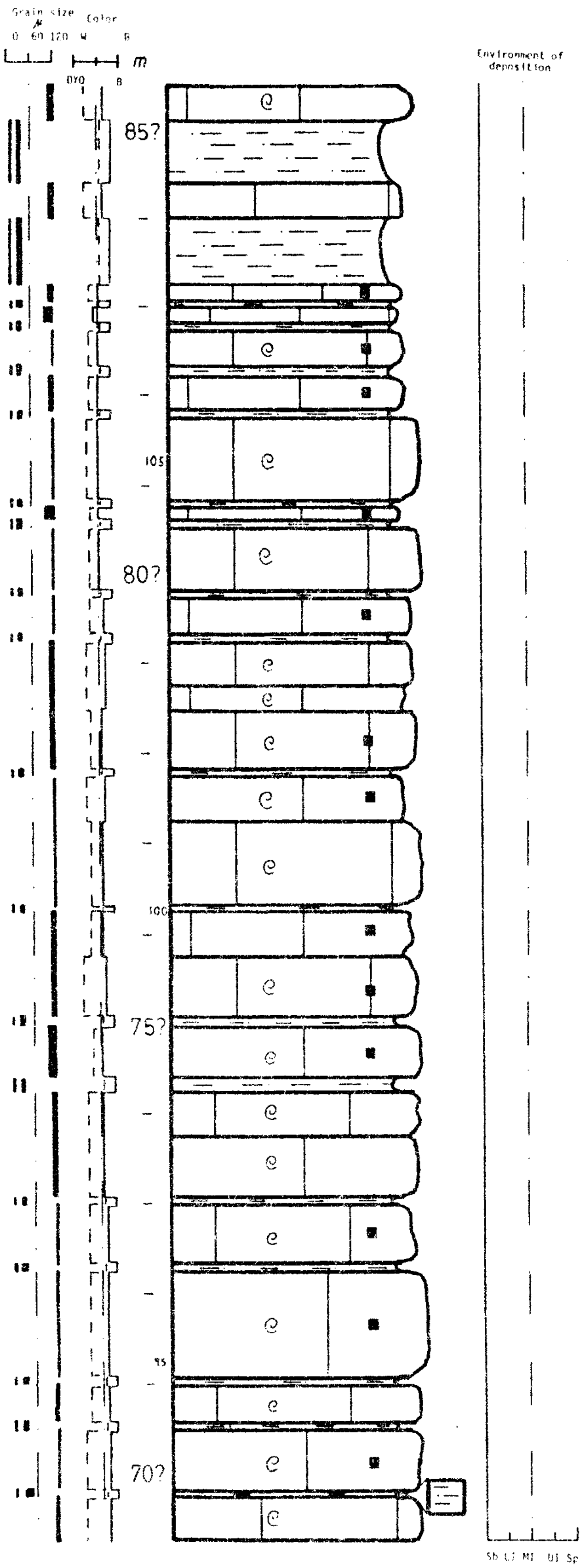


Fig. 9.25 (VII).- Town Farm Bay, North Ferrisburg, Vermont.

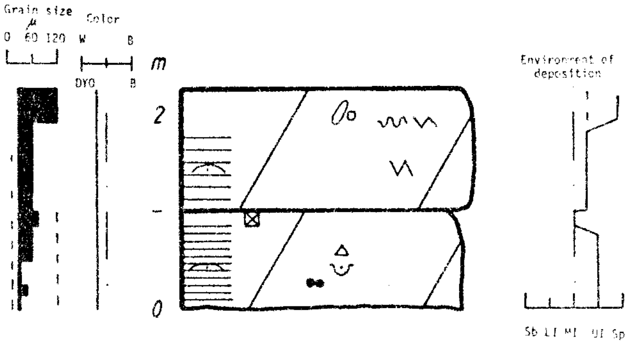


Fig. 9.26.- Valcour, New York.

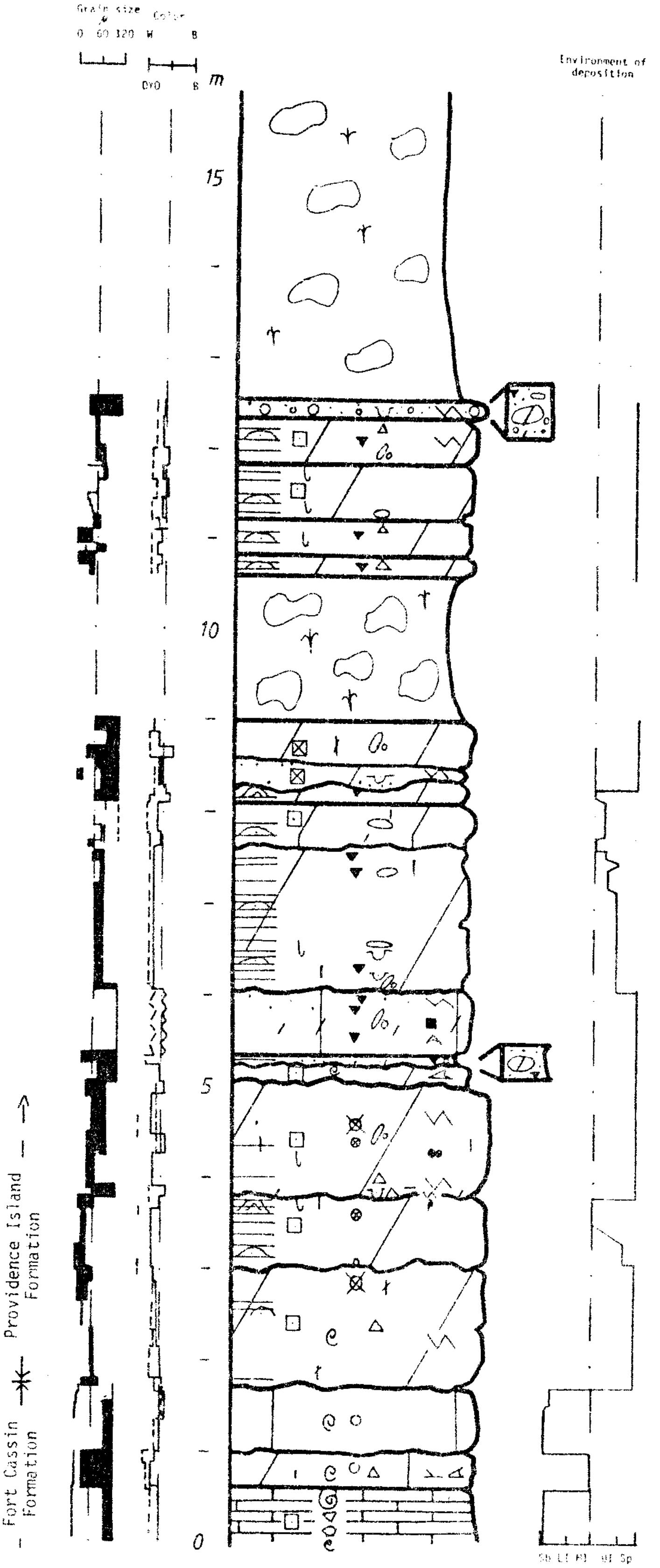


Fig. 9.27 (I).- Providence Island, Vermont.

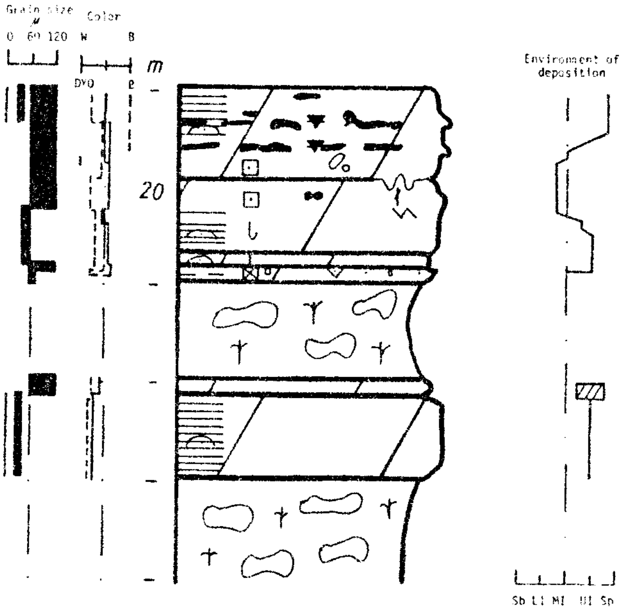


Fig. 9.27 (II).- Providence Island, Vermont.

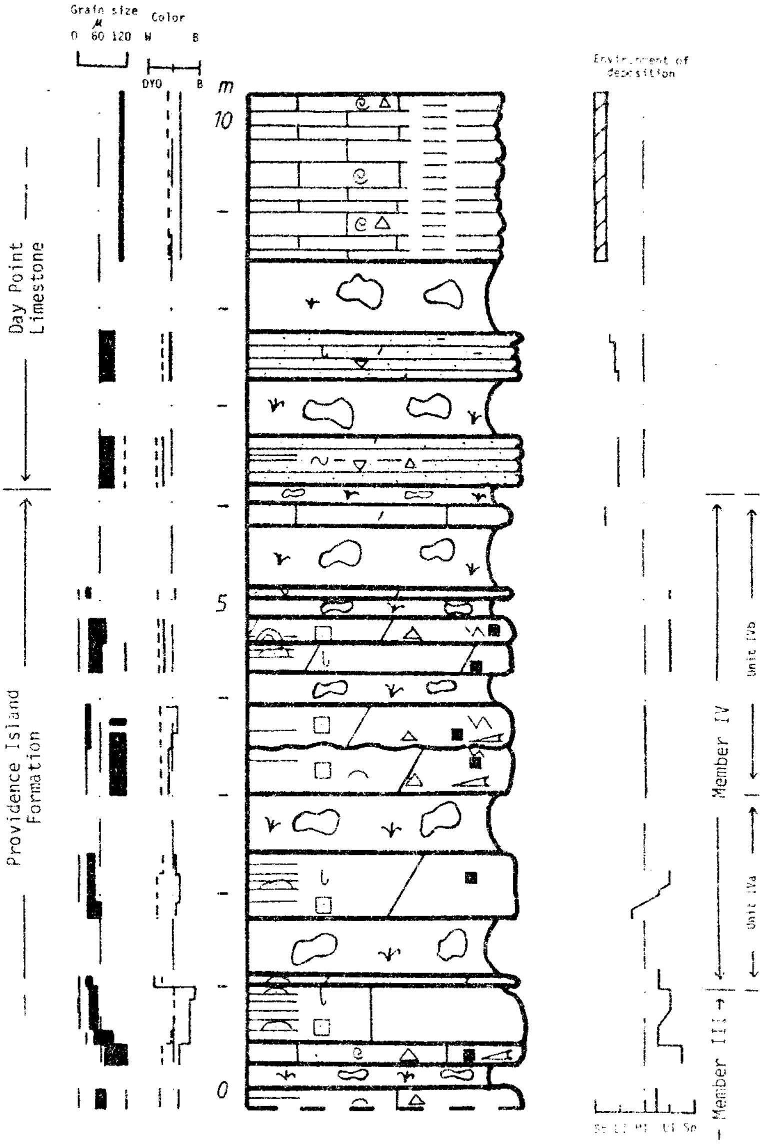


Fig. 9.28.- South Hero, Vermont.

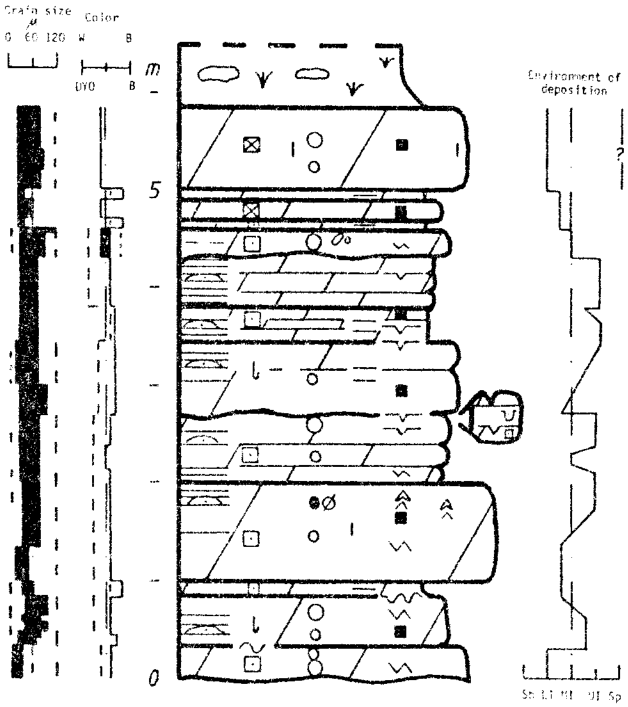


Fig. 9.29.- Saranac River, Plattsburgh, New York.

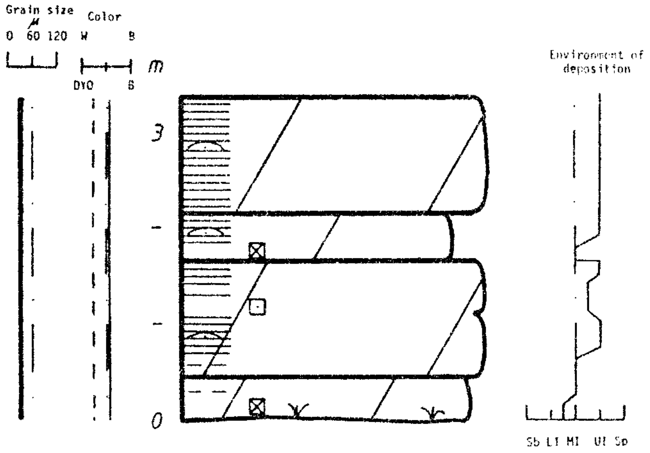


Fig. 9.30.- Beekmantown (locality A), New York.

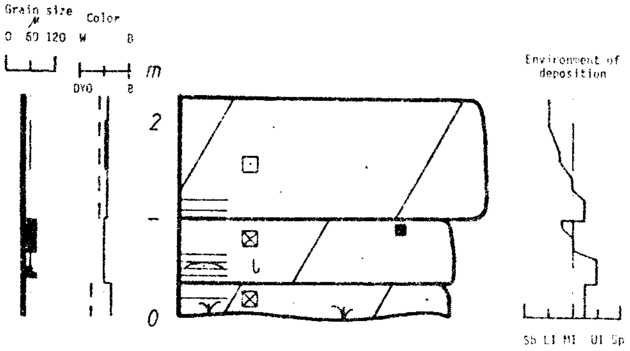


Fig. 9.31.- Beekmantown (locality B), New York.

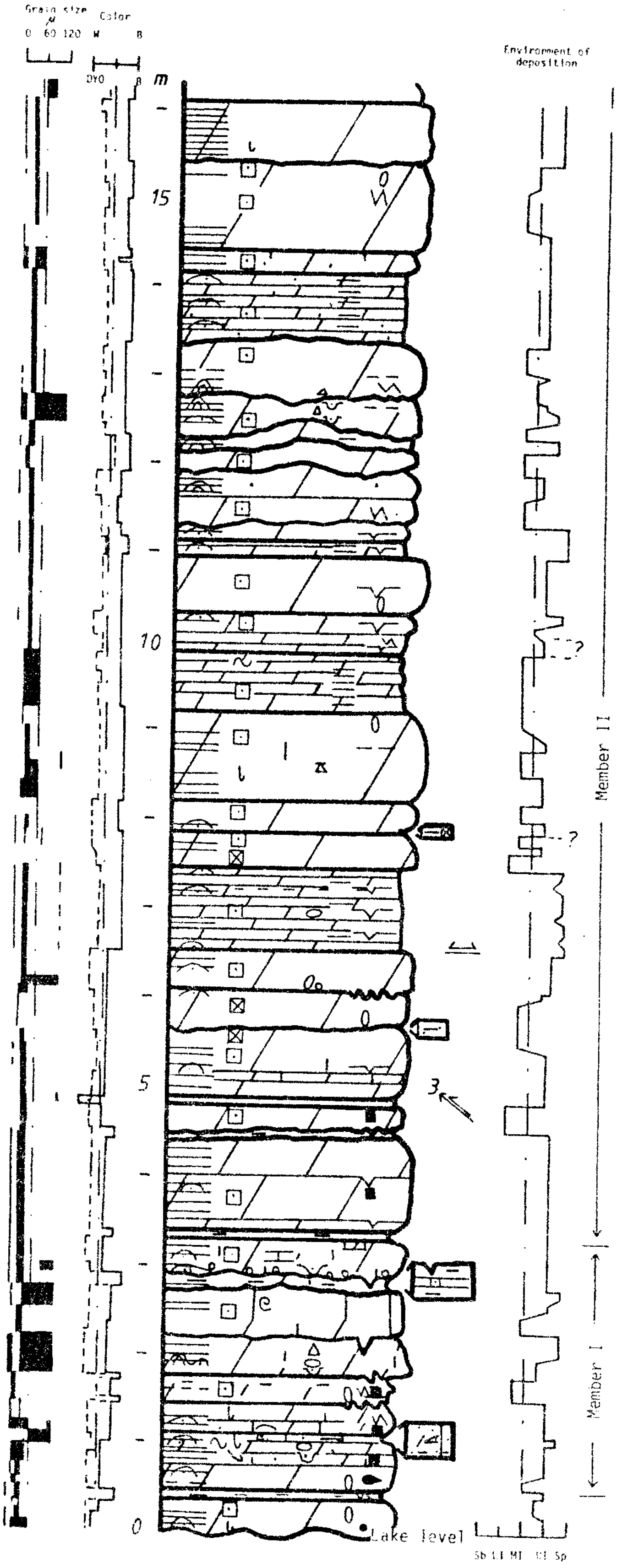


Fig. 9.32 (I).- Isle La Motte, Vermont.

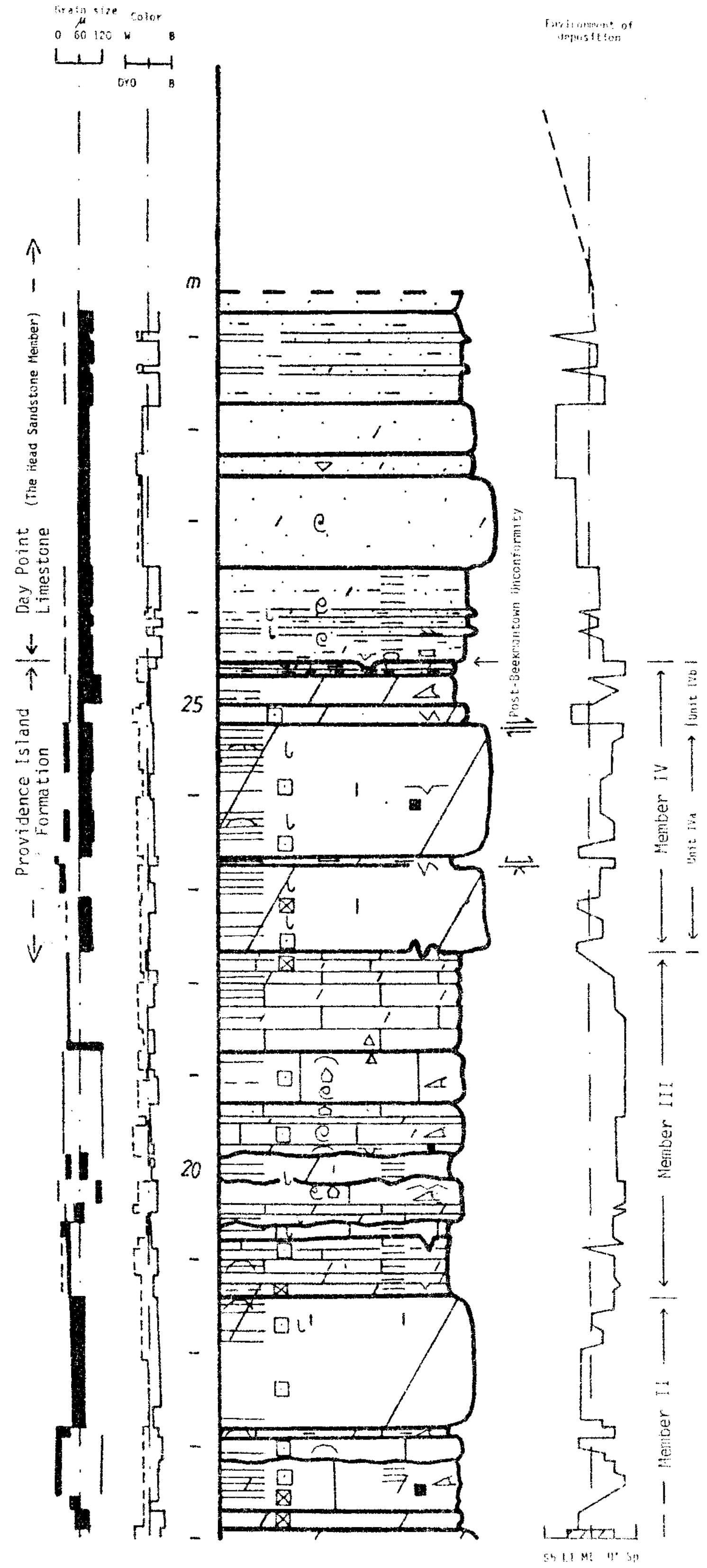


Fig. 9.32 (II).- Isle La Motte, Vermont.

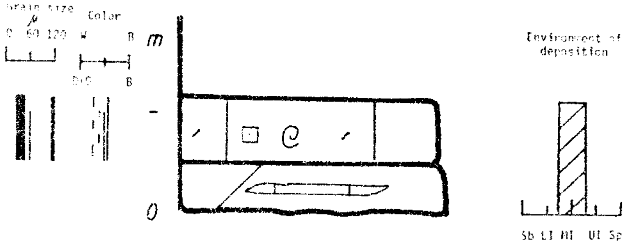


Fig. 9.33.- Napierville, Quebec.