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Peat–marl deposition in a Holocene paludal-lacustrine basin—Sucker Lake, Michigan

KATHY L. TREESE* *and* BRUCE H. WILKINSON

Department of Geological Sciences, The University of Michigan, Ann Arbor, Michigan 48109, U.S.A.

ABSTRACT

Exceptionally thick (over 15 m) deposits of peat which fill the northern end of Sucker Lake basin in north-central Michigan document the volumetric importance of allochthonous organic material in a modern coal-forming environment. Organic debris that originates in, and is derived from, a highly vegetated floodplain immediately upstream is deposited as a lakeward-prograding lobe that exhibits features typical of most lacustrine Gilbert deltas, but is composed almost entirely of organic material. This system overlies an additional 7 m of nearly pure, brecciated lacustrine carbonate, deposited as shallow lake-margin benches and emplaced into the deep basin centre by gravity sliding prior to deltaic progradation.

In the southern end of the basin, bottomset beds of fine silt-size organic phytoclasts onlap distal facies of progradational bench carbonates, which originate (in shallow water) through calcite encrustation about stems of the dominant macrophyte *Chara.* With continued sedimentation, a stratigraphic succession in which allochthonous organics will overlie pure, allochthonous lacustrine carbonates and in part be overlain by autochthonous carbonates will characterize the northern end of this Holocene system. In the southern end around the basin margins, however, autochthonous carbonates will entirely underlie allochthonous organics.

Numerous continuous cores (up to 22 m) through these units document: (1) the importance of sources of allochthonous organic debris in modern coal-forming complexes, (2) the genetic relationship between nearly pure calcareous and nearly pure carbonaceous facies within these paludal-lacustrine settings, and (3) the complexity of interrelationships between the several component facies within such continental sedimentary systems.

INTRODUCTION

Although lacustrine deposits are found throughout the rock record, few comprehensive studies of the geometry of modern lake facies have been carried out. In order to make valid interpretations of ancient lacustrine environments, however, a thorough understanding of processes and sedimentary products in a variety of modern lake settings is necessary. To this end, Sucker Lake in north-central Michigan was chosen to evaluate the texture, composition, thickness, and distribution of the various component facies which comprise a temperate-region lacustrine system. This basin is an excellent area for such a study because: (1) it has remained completely undeveloped as a residential or recreational area, (2) its relatively small size allows for a high density of cores by which to sample sediment variability in the system, and (3) Sucker Lake has received, and is receiving, considerable volumes of both autochthonous carbonate and allochthonous organic material allowing for an evaluation of the relative sedimentological importance of these two processes.

Two general types of lakes comprise modern lacustrine systems: (1) lakes in which sediment is composed mostly of allochthonous terrigenous material, and (2) lakes in which sediment consists of authochthonous non-clastic material, either as saline playas in which such sediments may be composed mainly of argillaceous carbonates and evaporites, or low-salinity lakes in which relatively pure calcium carbonate is precipitated rapidly. Lakes dominated

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* Present address: Exxon Company, U.S.A., New Orleans, Louisiana 70121, U.S.A.

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by terrigenous input are by far the most common and probably the most thoroughly studied. In the rock record, however, sediments laid down in these lakes are commonly evaluated as component facies, such as deltas and beaches, and are less often considered as facies within a complex of lacustrine sediments. In contrast, modern playa lakes, common in arid regions of the world, have been more widely studied (Hardie, Smoot & Eugster, 1978, Hardie, 1968, Eugster & Hardie, 1978, and others), as have their ancient counterparts (Bradley, 1929, Eugster & Surdam, 1973, Eugster & Hardie, 1975, and many others).

Low-salinity, hard water lakes whose sediments are rich in carbonate have been less thoroughly investigated (e.g. Terleckey, 1974; Murphy & Wilkinson, 1980). Within such marl lakes, carbonate-rich sediment (90–95% $CaCO_3$) forms broad, shallow benches around lake margins which prograde basinward with time (Murphy & Wilkinson, 1980). Water depths over these bench surfaces rarely exceed 1·5 m, and benches may extend up to 25 m basinward before dropping off steeply into the deep basin centre. These lakes are found throughout temperate regions of the world, and occur commonly in the mid-western portions of the United States, especially in New York, Michigan, Minnesota and Indiana. Geographically their distribution is largely limited to south of 60° and to elevations of less than 1500 m (Kindle, 1929).

Marl lakes scattered throughout the lower peninsula of Michigan occupy kettles formed during retreat of the Wisconsin ice sheet from the area 13,700 to 13,000 years ago (Farrand & Escham, 1974). Early studies of marl lakes in this region stemmed from the use of marl in the cement industry (i.e. Davis, 1900, 1901, 1903; Blatchley & Ashley, 1900; Pollock, 1919), and included data on the distribution of marl deposits as well as speculations as to the mechanisms of carbonate precipitation (Russell & Leverett, 1903). In general, two mechanisms were proposed for the precipitation of calcium carbonate in temperate region lake systems. These were biologically induced precipitation (Pollock, 1919; Wetzel, 1960; Davis, 1900, 1901) and inorganic physiochemical precipitation (Kindle, 1929; Blatchley & Ashley, 1900; Brunskill, 1968; Terleckey, 1974). These are end member processes, with the actual mechanism in different systems commonly being some combination of the two.

GENERAL SETTING

Sucker Lake, a marl lake located in Isabella county, central Michigan, is one of six connected lakes which occupy a complex of coalescing kettle holes surrounded and underlain by Pleistocene calcareous till, gravel, and sand. Sucker Lake occupies two of these kettles, one of which is the deepest kettle in the complex. These depressions divide the lake into two basins, each having a maximum depth of slightly more than 5 m, separated by a sill at a depth of approximately 3 m (Fig. 1). This sill restricts circulation, causes the development of anoxic bottom waters, and allows for the preservation of organic matter. While the lake currently has a surface area of 40,000 m^2, the initial basin was over twice this size and considerably deeper. Sediment samples taken just above the Pleistocene surface in this kettle complex have been dated at 11,700 to 11,400 years, indicating that the basin flooded soon after the retreat of the Wisconsin ice sheet. Holocene sediments consist solely of regressive sequences, suggesting that the basin filled too rapidly for the transgressive deposits to be laid down. These facies also suggest that since the time of initial basin flooding, the lake level has remained fairly constant, undergoing only minor fluctuations.

Total sediment thickness data from 15 cores (12 around the lake margin and three in deep water), as well as data from nine holes that were not cored, were combined to construct a map of net Holocene sediment. This was done by contouring depths to Pleistocene based on our thickness data and the topographic expression of the subaerial Pleistocene basin margin, as elevation above sea-level. Depths on a bathymetric map were then also converted to elevations above sea-level, and the two maps were subtracted, yielding an isopach map of net Holocene sediment (Fig. 2). From this map it can be seen that the underlying Pleistocene surface follows the same general pattern as does the present sediment surface, and that thicker accumulations of sediment occur in the central portions of the two kettles. Sediment thickness reaches a maximum 22 m in the centre of the northernmost kettle, one of the thickest known accumulations of post-Pleistocene sediment in this region, exclusive of the Laurentian Great Lakes. A small stream, Sucker Creek, which drains a highly vegetated floodplain, flows into this end of the lake and transports large quantities of allochthonous organic material to the lake basin. We have termed this organic debris allochthonous phytoclasts, most of which are now being deposited at the mouth of the creek in the form of a small Gilbert delta.

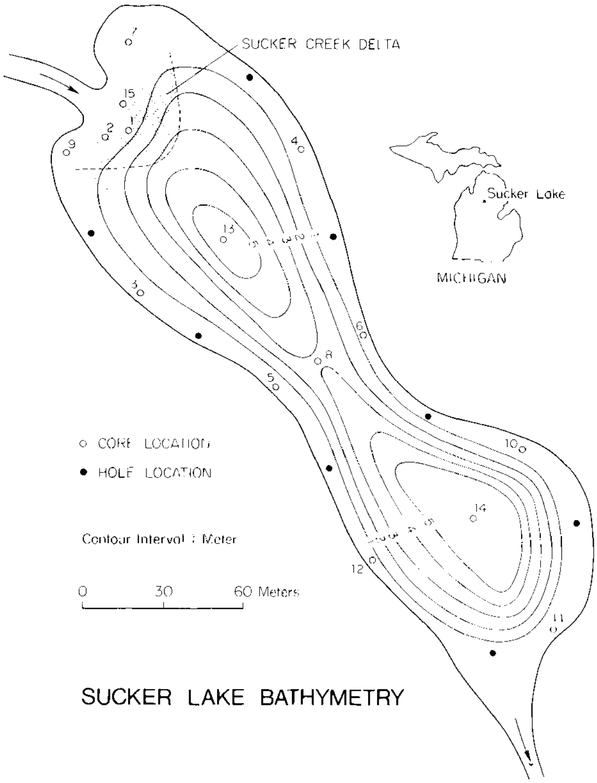


Fig. 1. Bathymetric map of Sucker Lake. Open circles are locations of complete Holocene cores and closed circles are locations of uncored holes. A Gilbert delta which progrades into the northern end of the lake is shown as the stippled area.

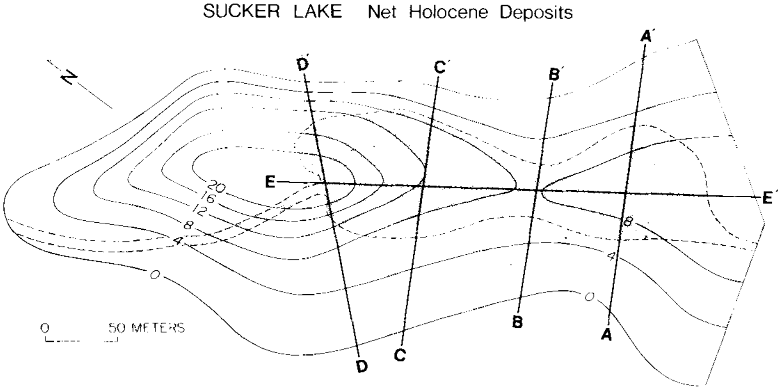


Fig. 2. Isopach map of net Holocene sediment in the Sucker Lake basin. The present shoreline is shown by the dashed line. Note that the thickest accumulations of sediment occur in the central portions of both basins and that the maximum sediment thickness occurs at the mouth of Sucker Creek. Lines A–A′ to E–E′ indicate the locations of cross-sections in Figs 7 to 11 respectively.

SUCKER LAKE SEDIMENTS

The sediments of Sucker Lake can be divided into three broad genetic groups; progradational marl bench carbonates, organic-rich progradational deltaic peats, and deposits which are transitional between the two. The occurrence of these extremely different types of sediment within this small basin gives rise to a complex series of facies relationships.

Marl bench deposits

Marl benches which encircle Sucker Lake consist of coarsening-upward progradational sequences. They comprise topset, foreset and bottomset deposits laid down on the horizontal bench platform, the inclined bench slope, and the horizontal basin centre respectively. The sediments are typical of marl bench deposits, average approximately 91% $CaCO_3$, and resemble those described by Murphy & Wilkinson (1980) from Littlefield Lake, located immediately south-east of the Sucker Lake basin. Marl bench sediments (cores 3, 4, 5, 6, 8, 10, 11, 12 and 14) occur as seven facies, which ideally, from top to bottom are: medium *Chara* sand, medium gastropodal *Chara* sand, fine laminated *Chara* sand, fine laminated gastropodal *Chara* sand, laminated gastropodal silt, ostracodal carbonate mud, and gastropodal carbonate mud. Molluscs consist primarily of the gastropods *Valvata tricarinota*, *Gyraulus deflectus* and *Amnicola integra*, and common bivalve, *Sphaerium partumeium*.

Bench platform deposits

Medium Chara *sand.* This sand, when present, occupies the uppermost portion of marl bench cores, is medium tan in colour, and consists of medium sand as carbonate-encrusted stems of the lake alga *Chara* (Fig. 3A). *Chara* oogonia, gastropods, and plant fragments are also present, although in minor amounts. These units are always massive, never exceed 2 m in thickness, and presently occur over many marl bench platform surfaces.

Medium gastropodal Chara *sand.* This facies is nearly ubiquitous in marl bench cores, and either occupies the uppermost portion of cores or immediately underlies medium *Chara* sand which it resembles, but is light tan in colour and contains a larger fraction of gastropod shells. It is always massive. Thicknesses of this facies range from 1 to 2 m, with thicker sections occurring where *Chara* sand is absent. It may also occur on the bench platform surface.

Bench slope deposits

Fine laminated Chara *sand.* This sand always occurs below one, if not both the above lithologies, or may be found surfacing bench slopes. It consists mainly of

Fig. 3. Core segments through typical Sucker Lake facies. Each core is 5 cm in width.

(A) Medium *Chara* sand. This facies is primarily composed of calcite *Chara* stem encrustations and rare gastropod debris. The massive unbedded appearance of this core segment is typical of this carbonate sand facies.

(B) Fine laminated *Chara* sand. Couplets within this facies consist of coarser (light) layers which grade upward into finer (dark) silt laminae. Couplet boundaries are commonly sharp contacts. The vertical groove is an artifact of core preparation.

(C) Laminated gastropodal silt. This facies lacks *Chara* encrustations but contains gastropod and bivalve shells. Note the faint horizontal laminations which typically occur throughout this homogeneous carbonate mud.

(D) Ostracodal carbonate mud. This facies, encountered only in the centre of the southernmost basin, is generally laminated, but may be homogeneous or bioturbated. The thin horizontal cracks developed during core dessication prior to being photographed.

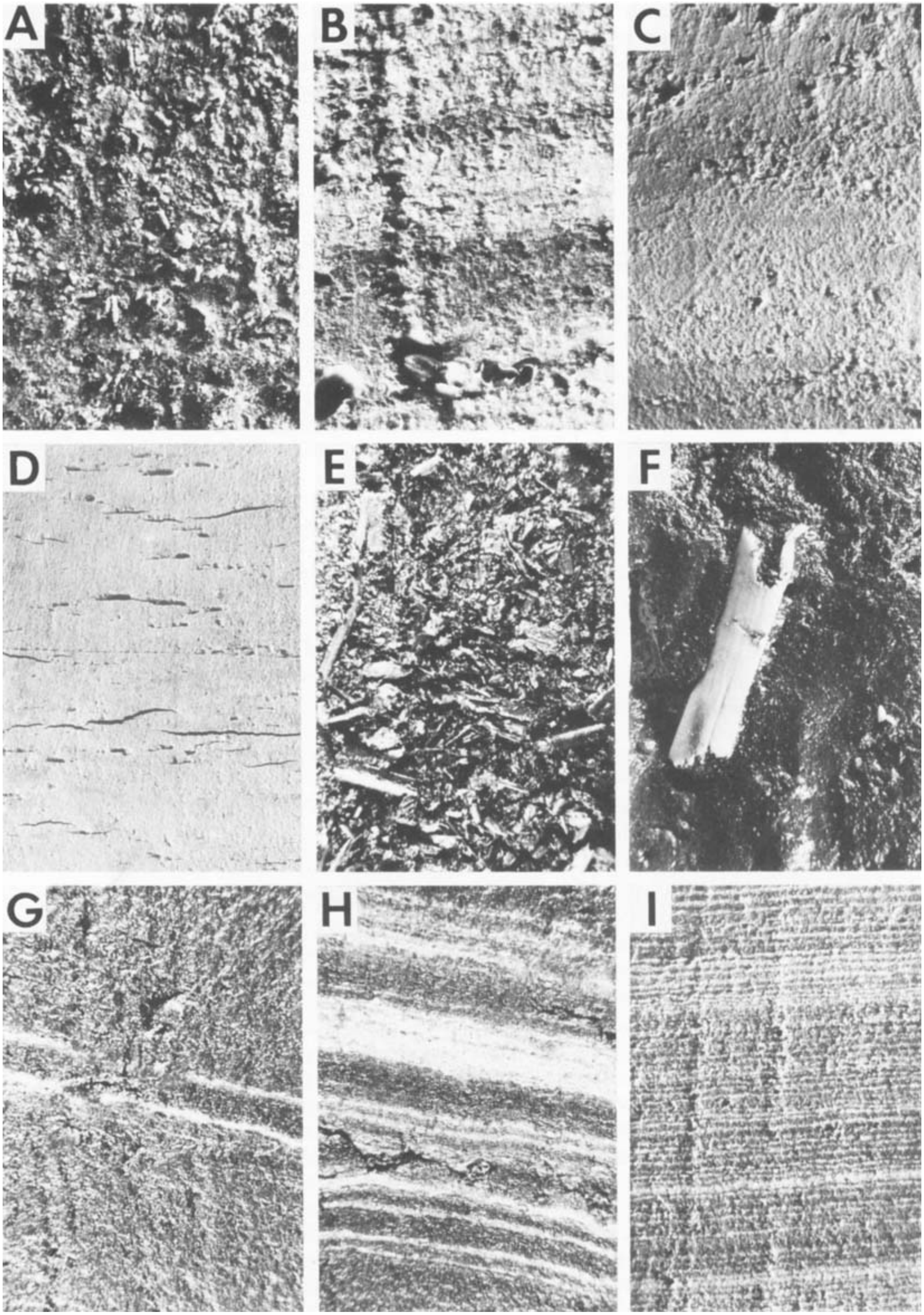
(E) Coarse allochthonous phytoclasts such as these comprise proximal deltaic sediments at the mouth of Sucker Creek. These are the coarsest organic clasts in Sucker Lake and are deposited as deltaic topset beds.

(F) Fine allochthonous phytoclasts. Silt-size organics (dark) are deposited as prodeltaic muds or bottomset beds away from the delta in deep lake centres. They may contain rare plant fragments such as the one shown here (light) which floated towards the lake basin, became water-saturated, and sank to the soft mud bottom.

(G) Varved mud consisting almost entirely of pure organic silt. Couplets in such organic-rich sediments are not readily visible owing to the small variation in colour between individual laminae. Note the two thin carbonate laminae in the centre of the photograph.

(H) Varves composed of carbonate-organic couplets. Note the sharp basal contacts of light carbonate laminae, and their gradational upper contact with dark organic laminae. Varves such as these occur stratigraphically above couplets of nearly pure carbonate and below more organic couplets.

(I) Varves composed primarily of carbonate. This field of view contains 65 annual couplets.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laminated fine-grained sand and silt, in which laminae are composed of alternating layers of light tan fine carbonate sand and medium grey carbonate silt (Fig. 3B). The light tan layers are always the thickest and are composed primarily of encrusted *Chara* stems, generally oriented with their long axes parallel to the laminae, which dip basinward at angles of up to 20°. That the long axes of *Chara* encrustations are commonly oriented parallel to dip, suggests gravity deposition on bench slopes, perhaps by turbidity currents. Grey silt layers lack *Chara* encrustations and shell fragments, and were probably deposited from suspension between turbidity current events. Thickness of this facies ranges from 0·7 to 2·5 m.

Fine laminated gastropodal Chara *sand.* This facies resembles fine laminated *Chara* sand, contains considerably more gastropod shells, exhibits similar thicknesses, and probably was deposited under similar conditions. If both laminated sand facies occur in the same core, this lithology generally underlies laminated *Chara* sand, but the two may interfinger or even be transposed.

Basin centre deposits

Laminated gastropodal silt. This silt is commonly found as the basal unit in cores taken through marl benches and consists of very coarsely laminated medium to light grey carbonate (Fig. 3C). Laminae are up to 3 cm thick with the basal contacts of many exhibiting soft sediment deformation features. Fragments of gastropod and bivalve shells are common, and minor amounts of bioturbation may be evident. This unit is usually thin, rarely exceeding 1 m.

Ostracodal carbonate mud. This is a thin facies found only in the central portion of the southern basin. It is 65 cm in thickness, is light green-grey to grey in colour, and contains no *Chara* stems or shells. Coarse laminations up to 7 cm thick are common (Fig. 3D).

Gastropodal carbonate mud. This facies occupies the lower portions of the deep-water cores, is medium green-grey in colour and generally massive, but may exhibit rare crude laminations. This mud is moderately bioturbated and reaches thicknesses of 3·5 m.

Marl bench sedimentation

Facies which comprise marl bench sequences are nearly identical to sediments at comparable depths which occur on the bench surface, and as such, record bench progradation under conditions of constant lake level. Modern benches grow by precipitation of large volumes of low magnesian calcite on nearshore portions of benches, and build basinward through the lakeward transport and deposition of this carbonate material. Marl precipitation is primarily due to the action of the lake algae, *Chara*, which during photosynthesis remove carbon dioxide from lake water immediately surrounding their stems, shifting the carbonate equilibrium, and causing the precipitation of calcium carbonate encrustations. Some of this carbonate remains on the bench platforms, but much is transported basinward. Generation of carbonate in shallow nearshore settings and lakeward transport of these grains results in the growth of a lake-margin bench typical of marl lakes in this region. Medium carbonate sand facies, record deposition on, and progradation of, horizontal nearshore bench platforms. Fine laminated sand facies reflect gravity emplacement of finer fractions on steeply inclined bench slopes, while carbonate silt and mud facies record deposition of the finest carbonate fractions in horizontal basin centre settings. Some of the basin centre material may also be due to settling of carbonate formed by physiochemical precipitation in the epilimnion.

Progradation of these environments gives rise to the coarsening-upward sequence encountered in cores through benches fringing the southern margins of Sucker Lake. Similar trends and facies reported by Murphy & Wilkinson (1980) from Littlefield Lake, Michigan, suggest that such sequences are characteristic of temperate-region, calcareous, lacustrine systems.

Deltaic deposits

Allochthonous organic material is being deposited at the mouth of Sucker Creek in the northern end of Sucker Lake as a small Gilbert delta (Fig. 1). Deltaic sediments encountered in cores 1, 2, 7, 8, 9, 13, 14, and 15 comprise one facies, composed almost entirely of allochthonous phytoclasts. A typical core taken through the deltaic sediments exhibits a general trend toward finer grain size and increasing carbonate content with depth.

Allochthonous phytoclasts are composed of gravel (Fig. 3E) to silt-sized (Fig. 3F) plant fragments, which are transported into the lake by Sucker Creek which drains a highly vegetated floodplain. This facies is dark brown and may contain up to 70 wt % organic material. Carbonate content is often as low as 10 wt %, with the remainder being composed of non-combustible terrigenous material which is derived through the erosion of Pleistocene drift in headwater regions and is transported into the lake by Sucker Creek. Gastropods are common in this facies, and occasional layers of *Chara* stems may be found. *Chara* stems, however, are generally unencrusted or thinly encrusted with calcium carbonate relative to those found in bench sediments. This facies is generally structureless, contains ostracodes in the finer portions, and may reach 7 m in thickness.

Deltaic sedimentation

As with carbonate bench deposits, vertical sequences encountered in cores through the Sucker Creek delta are also represented at comparable depths by sediments on the delta surface, and record basinward progradation of the organic-rich system during constant Holocene lake level. Deltaic sediments are similar to their terrigenous counterparts from other systems in that they exhibit a coarsening-upward trend and consist of topset, foreset and bottomset beds, reflecting deltaic progradation lakeward as new organic material is transported basinward by the creek. The coarsest phytoclasts are deposited as topset beds, while finer phytoclasts are carried further basinward to be deposited as foreset or bottomset beds. The finest phytoclasts are now transported into the southern basin and are deposited on basin-centre carbonates as organic prodeltaic muds.

Varved deposits

A third type of sediment, transitional between fine carbonates of distal bench deposits and fine organics of prodeltaic deposits, is found in a number of cores (cores 1, 2, 7, 9, 13, and 15) in the northern lake basin. These sediments are composed of varved mixtures of carbonate and organic mud.

Varved sediments occur as a spectrum of compositions and structures depending on their horizontal and vertical location within the basin. They range from varves composed almost entirely of organic debris to those composed of nearly pure carbonate (Fig. 3G, H and I). Organic-rich varves are found higher in cores and closer to the Sucker Creek delta than are carbonate varves. Prodeltaic phytoclasts become varved at depths of approximately 5 m, but the first carbonate varves do not occur above depths of 7 m. Most varves however, are intermediate in composition.

Typically, carbonate laminae are thin, medium tan in colour, and grade up into dark brown organic layers. Basal contacts of carbonate laminae with underlying organic layers are always sharp. The relative thickness of carbonate laminae increases with increasing depth in cores, while the thickness of varve sets decreases. In other temperate-region lakes with similar sediments, the timing of couplet deposition has been confirmed by studies of individual laminae in which carbonate laminae contain only spring and summer pollen and diatoms, while organic laminae contain winter to early spring forms (Tippett, 1964).

Varve sedimentation

Unlike bench carbonates and deltaic organics, varved sediments are no longer being deposited in Sucker Lake. The numerous couplets encountered in the lower portions of some cores record annual deposition in the deeper-water portions of the northern lake basin only during earlier stages of basin filling. As such, the processes which gave rise to variations in laminae composition can only be inferred for this system.

Mechanisms for varve deposition are complex, as different processes were most likely responsible for the deposition of pure organic and pure carbonate varves. Carbonate varves in temperate region lakes typically result from the seasonal precipitation of calcium carbonate, with calcite forming during warm summer months, and organic material settling out of suspension at other times of the year. Conversely, varves composed entirely of organics probably orginated through differential settling of material transported from the creek, with differences between layers reflecting their size and terminal settling velocity. Varves of intermediate composition formed by a combination of these two processes.

Likewise, typical vertical transitions in Sucker Lake cores from thin carbonate-rich varves to thicker organic-rich varves records a temporal and spatial shift of varved subenvironments across the lake basin through time. Because organic debris are only delivered to the northern end of the lake basin, and because net Holocene sediment thicknesses record higher rates of deposition in the basin's northern end (Fig. 2), we conclude that this vertical transition in varve composition and thickness records progradation of organic-rich deltaic sediments southward through time.

GRAVITY PROCESSES

Early Holocene basinward transport of allochthonous blocks of shallow-water carbonate by gravity sliding has served to alter significantly the stratigraphic sequence of sediments which now fill the Sucker Lake basin. Typically, these shallow-water blocks underlie and are intercalated with deep-water varved muds and distal bench carbonates in the stratigraphically lowest part of the basin-fill. They occur throughout the central axis of the system and may comprise a significant thickness of basin-centre sequences. In the northern basin for example, allochthonous shallow-water carbonate blocks, deposited in waters only a few metres deep, are directly overlain by varved carbonates which were laid down in water depths of 18·5 m, the deepest water units encountered in Sucker Lake basin (Fig. 4).

For the most part these blocks are composed of medium carbonate sand, nearly identical to sand seen in the two uppermost bench facies. Contacts between allochthonous carbonate masses and surrounding sediments are always sharp, and some contacts show loading features. Commonly, blocks are brecciated and may incorporate small clasts of deeper-water facies such as varved carbonate mud.

In addition to allochthonous blocks of carbonate sand, in place soft sediment deformation has greatly disrupted Sucker Lake sediments, the deeper-water facies in particular. Common features include what are inferred to be large folds. A long core in the northern basin for example, encountered 80 cm of varved organic mud in which the bedding was nearly vertical (Fig. 4). Other soft-sediment features include small folds, faults, loading on unit contacts, and numerous injection features (Fig. 5).

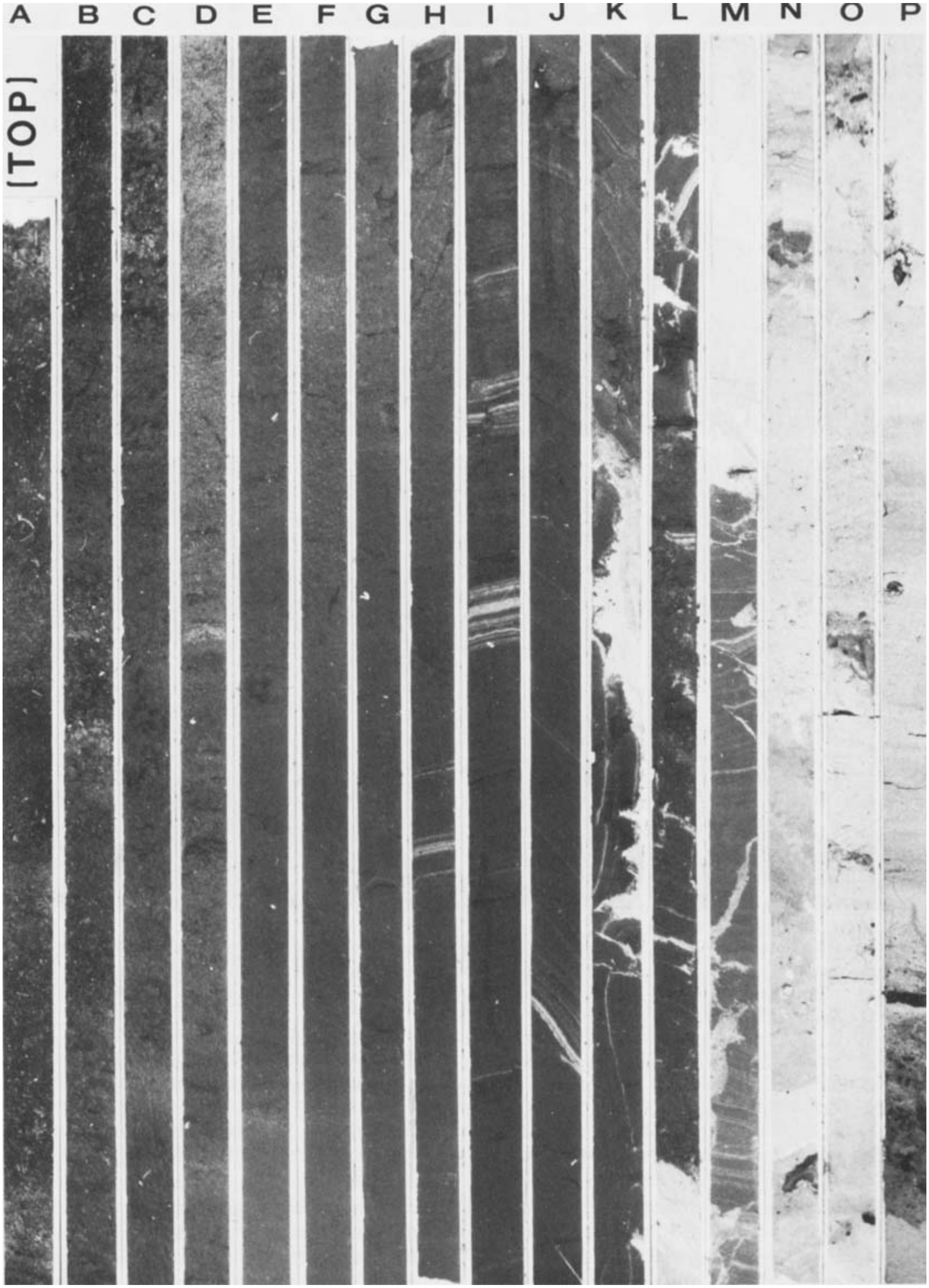
VERTICAL TRENDS IN CLAST SIZE AND COMPOSITION

Representative cores of both marl bench carbonates and deltaic organics were analysed at 50 cm intervals to quantify variations in grain size and composition. Grain-size analyses were done by wet sieving gravel, sand, and silt and clay fractions. Chemical analyses were carried out by a modified version of Dean's (1974) loss on ignition method. This technique gives weight percent organic, carbonate, and non-combustible material, provided samples are relatively low in clay. Sucker Lake sediments are nearly clay-free.

Bench sediments exhibit a nearly constant composition with depth. Within the upper 1·5–2·0 m, where phytoclasts are interlayed with carbonate, both organic and carbonate content are extremely variable, but are relatively constant below this depth. Grain-size relationships resemble those reported by Murphy & Wilkinson (1980) for such progradational carbonates, with grain size decreasing with increasing depth in the core, from medium sand near the top to fine sand and silt near the bottom.

Deltaic sediments show a similar coarsening-upward trend, but variations in composition are more pronounced in these sediments than in marl benches

Fig. 4. Photograph of core 1 (Fig. 1) taken from the northern end of the basin. This is the longest continuous core recovered from Sucker Lake, penetrating a total Holocene sediment thickness of 22 m. Each of the 16 core tubes shown here are 5 cm in width and approximately 120 cm in length owing to compacting of organic phytoclasts during core extrusion. From the top of the core the sequence consists of: (1) a progradational deltaic sequence of gravel to coarse sand phytoclasts (Tube A to the bottom of Tube F); (2) a varved sequence beginning in fine, nearly pure organic phytoclasts (top of Tube G) grading downward into organic varves with sporadic carbonate varves (bottom of Tube L); (3) a block of allochthonous *Chara* sand, deposited in a shallow bench setting and emplaced by gravity prior to deltaic progradation (108 cm in Tube L to 45 cm in Tube M); (4) continuation of the varved sequence, with organic-carbonate varves (lower portion of Tube M) grading downward into nearly pure carbonate varves (top 23 cm in Tube N); and (5) a series of seven allochthonous blocks of *Chara* sand, laminated silt, carbonate mud, and pebbles of varved carbonate, which were in part derived from lateral bench sequences and emplaced into the deep basin centre as the oldest Holocene units in this portion of the lake basin. These allochthonous carbonates overlie Pleistocene glacial gravels first seen at 87 cm in Tube P. Note the coarse phytoclasts in Tubes A and B, the finer phytoclasts in Tubes E and F, the first carbonate laminae at 81 cm in Tube G, the increasing inclination of varved sediments from nearly horizontal at 78 cm in tube H to nearly vertical in the lower portions of Tube K, the brecciated nature of varved muds throughout the central portion of Tube L, the upper allochthonous carbonate block (white) in the bottom of Tube L and the top of Tube M, the transition of varve compositions from organic-carbonate varves (in the lower portions of Tube M) to nearly pure carbonate varves (in the top of Tube N) and the thick sequence of allochthonous bench carbonates which comprise most of Tubes N, O, and P. As such, this core consists, from bottom to top, of allochthonous bench carbonates, autochthonous varved muds, allochthonous bench carbonate, varved organics, and a coarsening-upward progradational deltaic sequence of allochthonous phytoclasts.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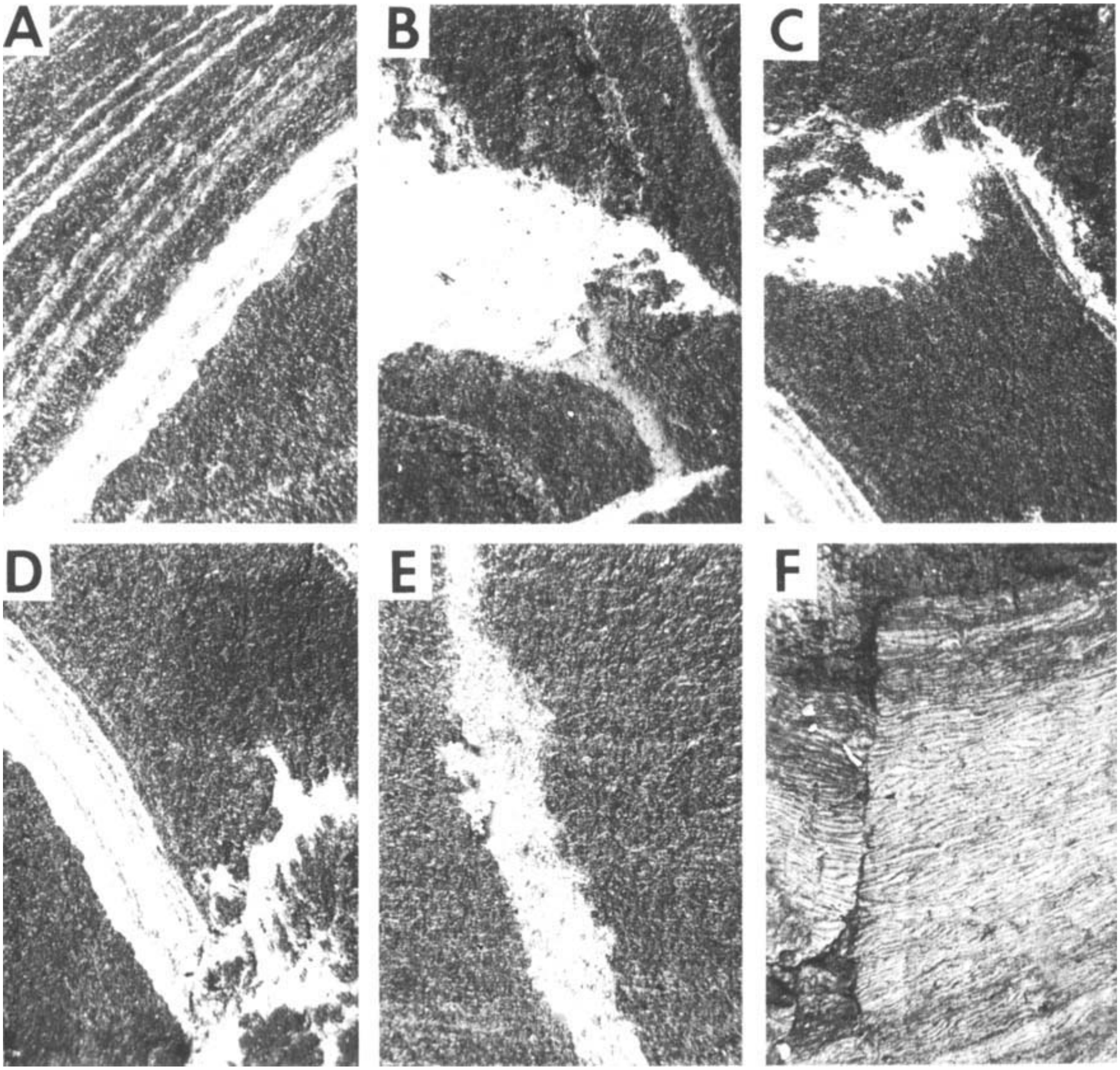

Fig. 5. Deformation features developed in Sucker Lake facies. Each core segment is 5 cm in width and is from core 1 (Fig. 4).

(A) Folded varved organic and carbonate muds. Note the sharp basal contact of the thickest carbonate laminae (white) which grades upward into the overlying organic laminae. Also note the small flame structures developed on the upper surface of the lowest organic layer. Tube J, 95 cm.

(B) Injection of allochthonous shallow-water carbonate sand along a small fault developed in deep water organic varves. Note the right lateral offset of the two nearly vertical carbonate laminae which parallel this core segment. Tube K, 84 cm.

(C and D) Folded and brecciated organic and carbonate laminae exhibiting injection of carbonate sand along faulted contacts. Note that (C) overlaps the top of (D). Tube L, 14 cm.

(E) Coarse carbonate sand dyke cutting finely varved carbonate and organic mud. Tube M, 84 cm.

(F) Faulted varves of autochthonous carbonate deposited in the deeper portion of the northern lake basin. Tube N, 11 cm.

(Fig. 6). Organic content decreases with increasing depth in the deltaic sequence from approximately 60 wt % at the surface to about 10 wt% at the base. Conversely, carbonate content increases with an increase in depth. Non-combustible material is less variable, but in general increases with depth.

These trends in size and composition record the progradation of deltaic organics southward into a

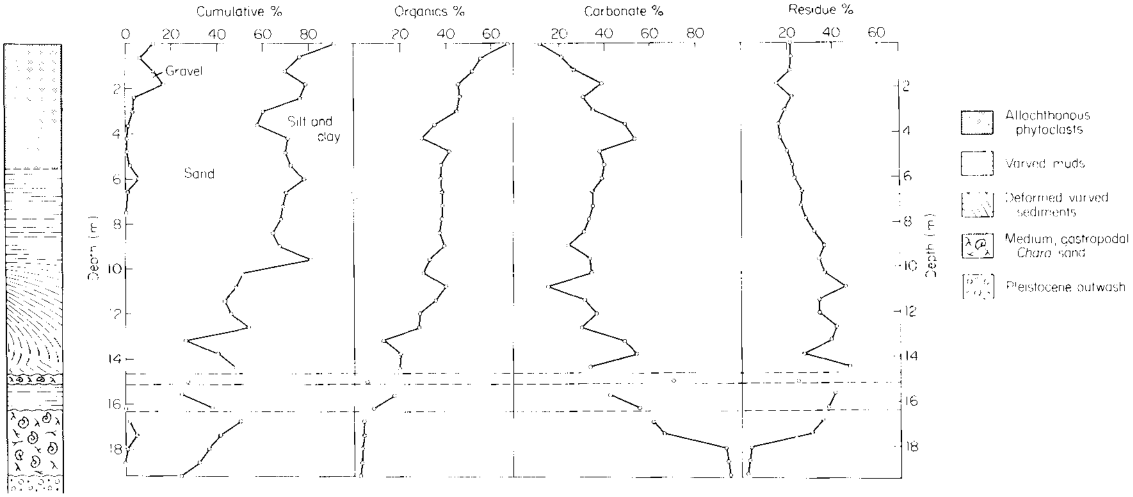

Fig. 6. Grain-size and sediment composition data for core 1 (Fig. 4). The dashed lines delimit allochthonous blocks of shallow-water bench carbonates which do not record vertical trends in the regressive deltaic sequence which comprises most of this core. Note vertical trends from bottom to top of increasing grain size, increasing wt % organics, decreasing wt % carbonate and decreasing wt % terrigenous components. Nearly identical trends characterize surficial sediments in a transect from the southern lake basin northward up on to the delta.

carbonate-rich basin during filling of the Sucker Lake basin, with vertical increases in weight % organics and sizes of allochthonous phytoclasts resulting from the progressively increasing proximity of the mouth of Sucker Creek. The gradual increase in weight % terrigenous components (non-combustible residue) in the deeper portions of the lake basin are similar to those reported by Murphy & Wilkinson (1980), and reflect selective dissolution of carbonate components in the deep, cold, undersaturated, hypolimnic waters which existed in the central lake basin.

FACIES ASSOCIATIONS

While the relationships between component facies which comprise bench or deltaic sequences are relatively straightforward, simply reflecting progradation of either subsystem basinward, the facies relationships between deltaic and bench sediments are complex. In general, sequences along the southern basin margin and along the lateral margins of the lake consist of normal progradational marl deposits. Likewise, the northern end of the lake contains a large volume of regressive allochthonous phytoclasts. Within the central two basins however, transition zones exist between the two types of sediment. These relationships are best seen in cross-sections taken through various parts of the lake.

The southern lake margins consist of normal marl bench sequences while the basin centre contains distal carbonate mud overlain by fine allochthonous phytoclasts (Fig. 7). Slump blocks of bench material occur within the deep-water carbonate sediments. These facies associations clearly reflect a transition from carbonate deposition which typified the early Holocene history of this area to organic mud deposition which records approach of the southward-building delta at the mouth of Sucker Creek. Not only do all the cores along this transect become more organic-rich upward, but deeper-water carbonate muds which initially blanketed basin-centre settings are now completely overlain by organic prodelta muds. These relationships clearly demonstrate that the relative rates of autochthonous carbonate deposition became less than rates of allochthonous phytoclast deposition once deltaic progradation began to influence the southern lake basin.

The central portion of the basin (across the sill) contains similar facies except that basin-centre carbonates are missing, as water depths over the sill have always been too shallow for their deposition (Fig. 8). Similarly, the margins of the lake consist of progradational marl bench sequences but only contain three of the five most proximal facies.

Across the northern basin, margins consist of normal marl bench sequences, while the basin centre contains a thick sequence of varved carbonates and

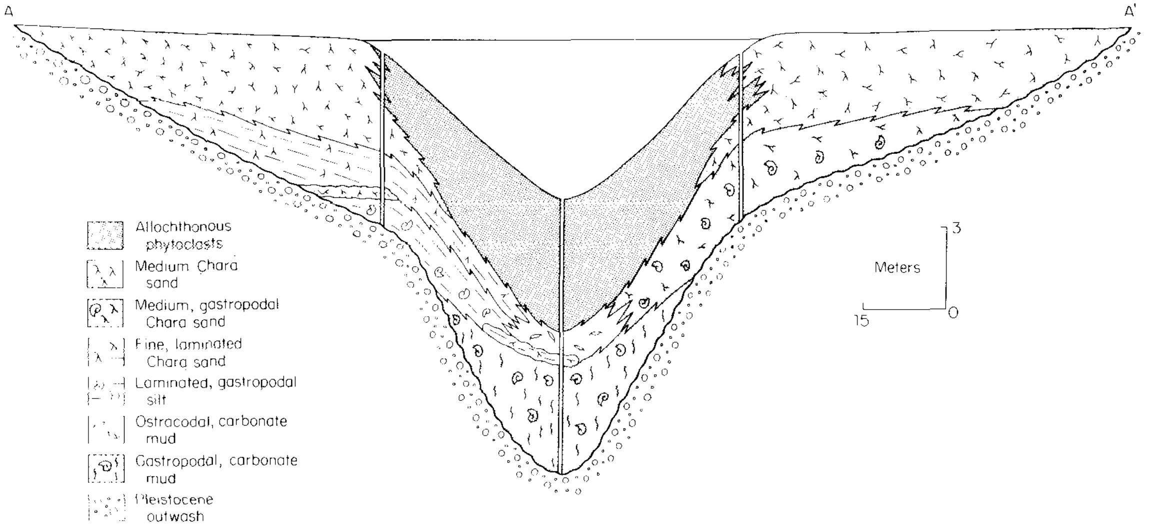

Fig. 7. Section across the southern Sucker Lake basin. Note that older Holocene units are regressive bench facies which record early basin filling by relatively pure lacustrine carbonate. These have been progressively overridden by organic prodeltaic mud which now blankets most of the southern basin floor.

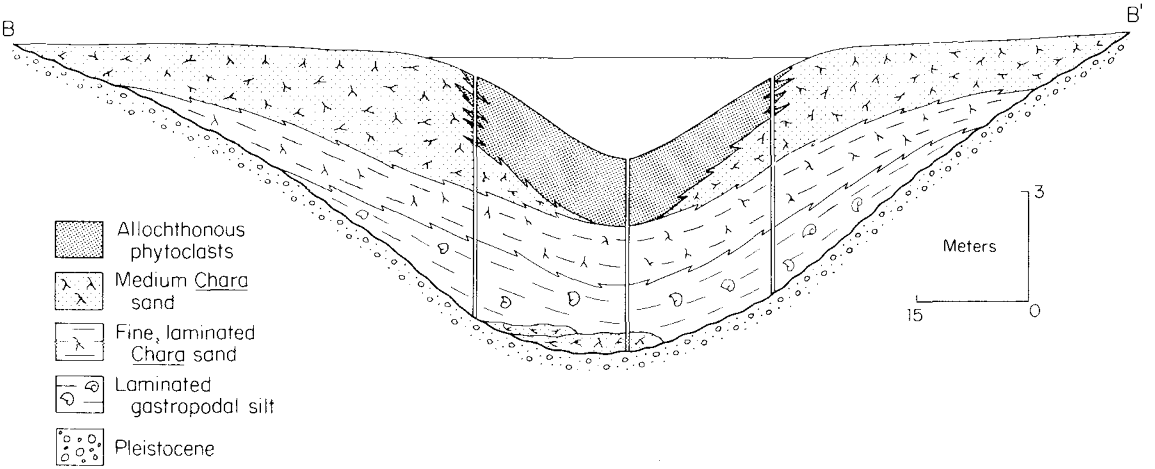

Fig. 8. Section across the middle of Sucker Lake, along the axis of the sill which subdivides the lake into two basins. Note that the facies associations within this section are similar to those across the southern basin but, because water depths across this sill have always been relatively shallow, bench carbonate only reflects deposition in bench slope and bench platform environments. Deep-water carbonate mud recording deposition in deeper lake areas, is not present under this portion of Sucker Lake.

organics which grade upward into fine structureless phytoclasts deposited as deltaic bottomsets (Fig. 9). In this transect, the transition between autochthonous carbonate and allochthonous organics reflects a change in the relative rates of Holocene carbonate and organic sedimentation in this portion of the Sucker Lake system. The transition between varved organic-rich mud in the basin centre and distal bench carbonates along the basin margins records progradation of calcareous benches over deep, more organic-rich basin centre muds during initial filling of the northern basin. Conversely, the contact between fine

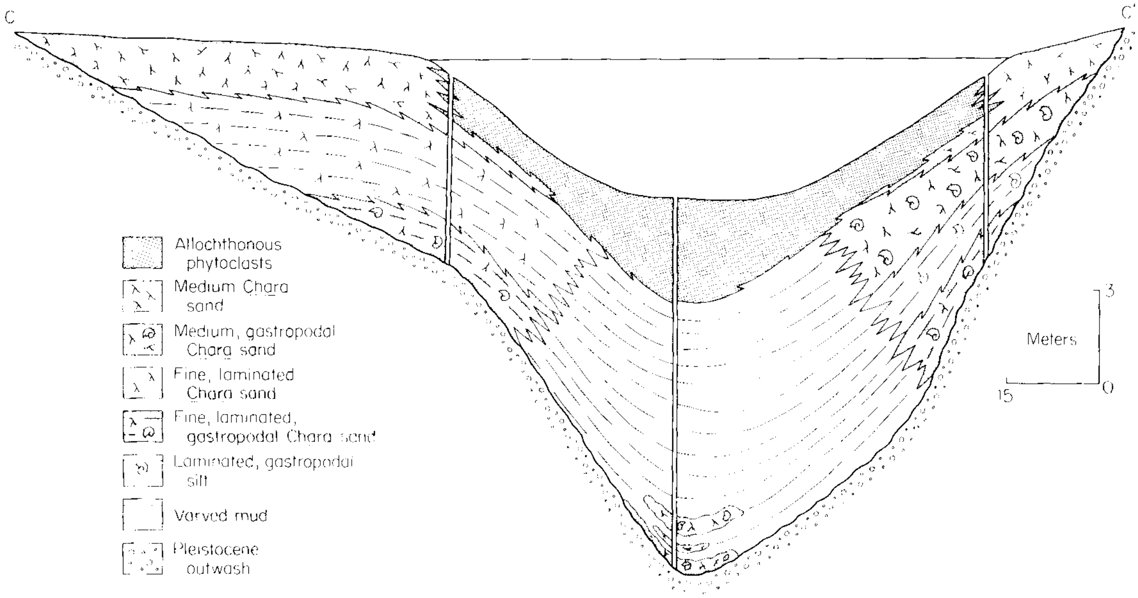

Fig. 9. Section across the northern basin. Note the nature of the transition between distal bench sediments and varved mud in the basin centre compared to the transition between proximal bench carbonate and fine phytoclasts deposited as deltaic bottomset mud. Older portions of this fill record lateral infilling of the basin by bench carbonate which prograded lakeward on to varved mud, whereas younger portions of the fill record deltaic progradation southward toward this portion of the kettle complex.

deltaic phytoclasts in the basin centre and proximal bench carbonates along the basin margins is similar to that seen in the more southern transects, and reflects more rapid deltaic progradation into this portion of the northern basin and onlapping of deltaic organics on to lateral bench carbonates (Fig. 9).

Similar associations are seen in a section across the mouth of Sucker Creek where the basin is nearly filled (Fig. 10). As in the other sections, marl bench carbonates occur along basin margins, but also comprise a number of large allochthonous blocks in the basin centre. These are overlain by varved muds which grade upward into coarser deltaic phytoclasts. Within the basin centre, varved muds occur higher in the basin-centre core than in either core taken through the basin margins. This spatial distribution of varved facies reflects the persistence of deep-water conditions within the basin centre prior to filling by deltaic organics.

It should be noted here that, unlike the southern three transects, in no instance do deltaic organics overlie bench carbonates in this section. The rates of carbonate production which gave rise to these (now inactive) bench sequences was always in excess of rates of deltaic phytoclast deposition in the basin centre. As a result, autochthonous lake-margin carbonates entirely overlie allochthonous organics.

Sucker Lake facies associations in longitudinal section are similar to those in transverse sections (Fig 11). Not surprisingly, sediments within the northern end of the complex are dominantly composed of organics comprising varved mud and deltaic phytoclast facies. These largely overlie allochthonous blocks of shallow water carbonate. To the south, sediments are primarily carbonate, recording basinward progradation of lateral benches which extend around the southern basin margin. Relationships between allochthonous organics and autochthonous carbonates are also similar to those in transverse sections. Distal bench fine carbonate sand and mud which blanket Pleistocene drift in the southern basin and across the central sill, grade laterally into, and override organic-rich varved mud which fills much of the northern basin. Deltaic phytoclasts on the other hand, overlie varved mud in the northern basin and carbonate silt over the sill and in the southern basin. These interfinger with, and override more proximal bench carbonate which makes up the southern lake margin. These distributions demonstrate that rates of autochthonous carbonate production and deposition were in

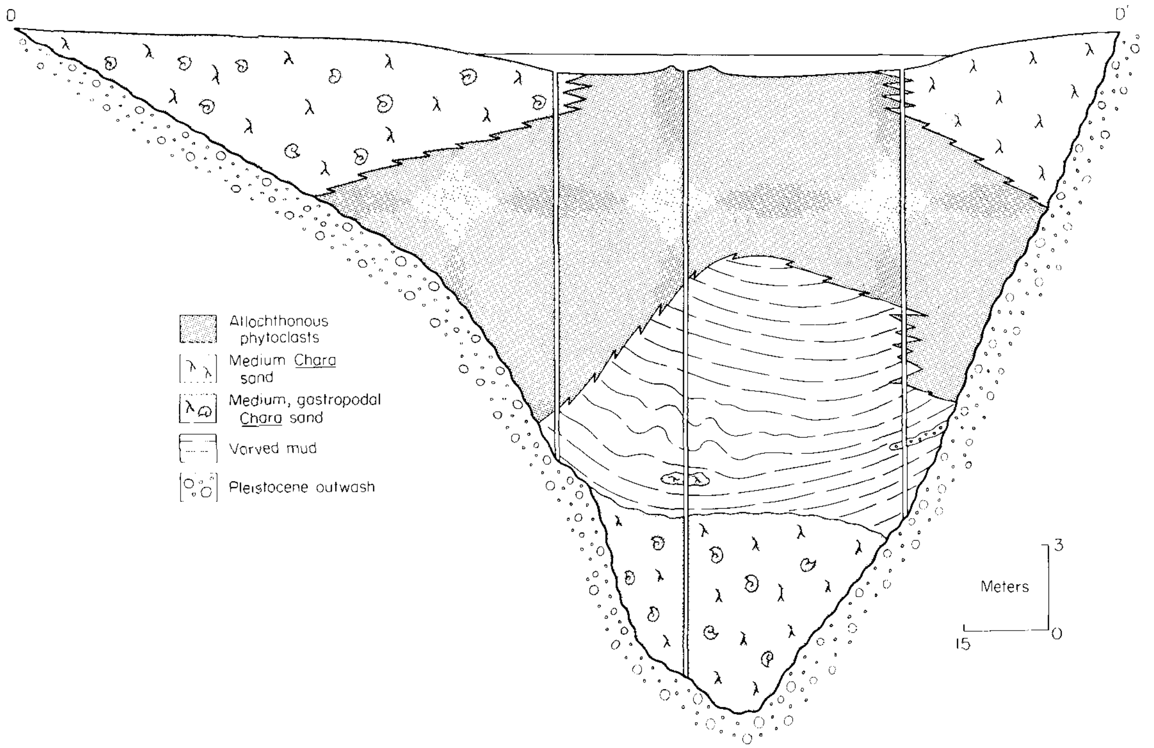

Fig. 10. Section across the Sucker Creek delta at the northern end of the lake. Note the nature of the contact between carbonate bench-sediment and basin-centre deltaic organics, and the large thickness of allochthonous lake-margin bench carbonate in the central portion of the basin.

excess of rates of organic phytoclast deposition early in the lake's history, but gradually became subordinate, such that much of the lake floor and distal bench segments are now blanketed with fine organic mud.

DISCUSSION AND CONCLUSIONS

Sucker Lake, a fairly typical lacustrine system in north-central Michigan overlies and is surrounded by a thick sequence of Holocene lake sediments deposited over the past 11,500 years. The variety of facies which comprise regressive sequences within this basin, and the complexity of facies associations which characterize past depositional events are somewhat surprising in a system of such modest size, but may be typical of larger lake basins elsewhere, and may serve as an excellent model for marl–peat deposition in temperate-region lacustrine systems.

Several important generalizations can be drawn from the origin, composition, and distribution of sediments within the Sucker Lake basin.

(1) Two genetically different sources of sediment have significantly influenced the composition and distribution of component facies within this lacustrine basin. Although allochthonous phytoclasts and autochthonous carbonates are equally represented volumetrically, each comprise sedimentologically distinct regressive sequences that characterize particular portions of the net Holocene deposit.

(2) Progradational lake-margin benches of autochthonous low-magnesian calcite which surround much of southern Sucker Lake are nearly identical to those reported from Littlefield Lake immediately to the south-west, and are probably typical of most regressive carbonate sequences developed in temperate region lacustrine systems. Coarsening upward grain-size trends and variable primary dips developed on horizontal bench platfoms, inclined bench slopes, and flat lake floors, are important textural features which characterize such carbonate sequences.

(3) Spectacular thicknesses (> 15 m) of silt- to pebble-size nearly pure organic debris make up much of the Holocene fill in the northern lake basin.

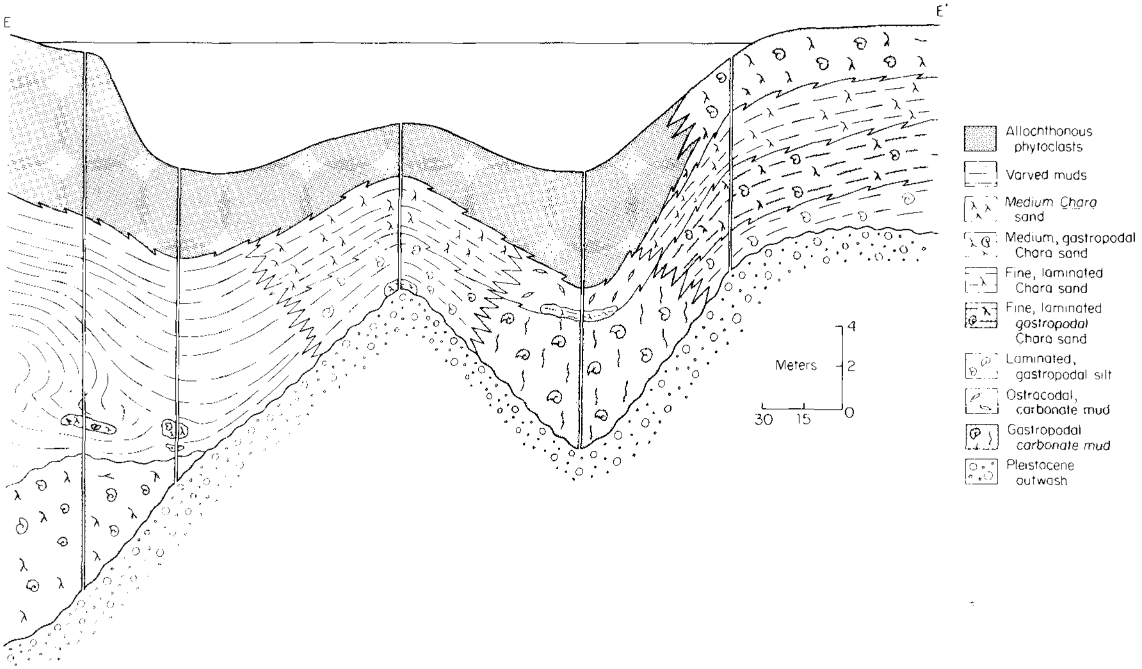

Fig. 11. Longitudinal section across the Sucker Lake basin. Note the distribution of component facies and the nature of the transition between calcareous and carbonaceous lithologies.

Deposited as a southward prograding delta, varved mud, bottomset silt, foreset sand, and topset gravel exhibit textures analogous to Gilbert deltas developed in terrigenous lacustrine systems, but compositionally have no known counterparts in modern lake systems. A such, they document the volumetric importance of transported organic material in these lake settings, and may serve as an attractive model for the deposition of thick allochthonous coals, known from more ancient continental sequences.

(4) Rates of autochthonous carbonate deposition relative to rates of allochthonous phytoclast deposition have not remained constant, and appear to have significantly decreased over the past 11,500 years in the Sucker Lake basin. Internal thresholds, not related to external controls (such as changing climate), have probably been largely responsible for this change. For example, allochthonous plant debris is largely derived from swamps immediately north (upstream) of the mouth of the Sucker Creek. These lush areas are now primarily developed on Holocene sediments which have largely filled the northern half of the northern basin (Fig. 2). It follows then that prior to extensive filling, these swamps were smaller, and as the basin continued to fill, this source of plant debris became larger. In other words, early Holocene basin filling through carbonate deposition has given rise to low swamps which produce additional non-carbonate sediment. With time these expand, producing additional volumes of allochthonous plant debris which at present largely blanket areas once receiving carbonate. Carbonate deposition in this instance is a self-destructive process, giving rise to the greater volumes of organic-rich sediments which now predominate in the lake floor. Long-term vertical and lateral changes in facies associations within such lake basins do not require coeval variations in external parameters.

(5) Allochthonous blocks of lacustrine carbonate, deposited on nearshore benches in shallow water, and subsequently emplaced into deep-water basin centres, comprise a significant portion of Holocene sediment in the Sucker Lake basin. The aerial and volumetric importance of these brecciated masses document the significance of subaqueous gravity sliding within such systems. Further, many of these blocks are texturally similar to intraclastic conglomerates reported from numerous ancient lake sequences which have been cited as conclusive evidence for shallow lakes, frequent subaerial exposure, and desiccation of lacustrine muds. Calcilithic conglomerates in lake carbon-

ates *per se* should not be used to interpret water depths.

(6) Facies associations within the Sucker Lake basin are complex, and change rapidly within relatively short distances. Similar facies are known from many coal–limestone complexes within continental systems such as Carboniferous cyclothemic sequences from North America, Europe and Asia. Despite the complexity of lateral and vertical variations in Sucker Lake sediments, these units record the gradual filling of a typical mid-western lake basin, and as such, may serve as a model for comparable ancient systems preserved in the rock record.

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