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ANALYSIS OF SEDIMENT AND SEDIMENTARY PROCESSES
IN PERENNIALY ICE-COVERED LAKE HOARE, ANTARCTICA

A Thesis

Presented to

The Faculty of the Department of Geology
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

Martha A. Schackman

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ABSTRACT

ANALYSIS OF SEDIMENT AND SEDIMENTARY PROCESSES IN PERRENNIALLY ICE-COVERED LAKE HOARE, ANTARCTICA

by Martha A. Schackman

Sediment cores from the bottom of ice-covered Lake Hoare, Antarctica, were examined for evidence of depositional controls on sedimentary structures and stratigraphy of the sediment. The ice cover causes sedimentation to be localized, resulting in the deposition of sand mounds and laterally discontinuous non-mounded sand layers on the lake bottom. The sedimentary processes in effect also result in the sorting and predominantly normal grading of some of the sand.

The mounds are interbedded with blue-green algal mats and the non-mounded sand. Mounds deposited by rapid sedimentation are steep-sided and large; those deposited by slower sedimentation are rounded and thin. These variations in sedimentation rates may be controlled by variations in both sediment supply and ice thickness. Possible controls on ice thickness include both climate and cyclic sediment loading and dumping, but simple sedimentary sequences produced by these factors have not been recognized.

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INTRODUCTION

The dry valleys of southern Victoria Land, Antarctica (Fig. 1), contain several lakes that are perennially ice-covered. The ice cover has a strong effect on lake processes by preventing development of wind-generated currents, restricting exchange of gases between the water and the atmosphere, and reducing the amount of penetrating light (Parker and others, 1981). The ice cover also affects deposition of clastic sediment in the lake. The sedimentary structures and stratigraphy of the lake bottom sediment, therefore, should reflect processes in the ice cover.

Lake Hoare (77°38'S, 162°53'E) is one of these perennially ice-covered lakes (Fig. 2). The lake bottom includes many sand mounds up to a meter in height that evidently are unique to this environment (Squyres and others, 1991). Clastic sedimentation in the lake is a discontinuous and localized process, and the recent stratigraphy was produced by the accumulation of sand mounds (Squyres and others, 1991).

The purpose of this study is to interpret the depositional processes that occur in the lake by examining in detail the sedimentary structures and stratigraphy of the lake-bottom sediment. Specifically, a search is made for evidence of how the mounds observed on the lake bottom are formed, and for information about processes in the

Figure 1. Site location map. Glaciers are stippled, lakes within Taylor Valley are shown in black. Lake Hoare is within the box, which shows the area covered by Figure 2.

Figure 2. Map of Lake Hoare and vicinity, with divehole locations. Bathymetric contours are in meters. Modified from Squyres and others (1991).

ice cover that result in development of the mounds. In addition, a search is made for evidence of changes in the ice that may be reflected in the lake-bottom deposits, and for evidence of external controls on the ice that may be recorded in the sedimentary sequences.

PREVIOUS WORK

For half a century after their discovery in the early 1900's, the perennially ice-covered lakes of southern Victoria Land remained virtually unstudied. In the late 1950's, limnological data began to be collected through 10- to 23-cm-diameter holes drilled in the ice, primarily for studying the water column. In 1978, research divers began working beneath the lake ice covers, allowing for more detailed limnological, biological and sedimentological studies (Wharton and others, 1989).

Limnological studies of the dry valley lakes in general have included investigations of physical processes (e.g., Henderson and others, 1966; McKay and others, 1985), those that are geochemical in nature (e.g., Green and others, 1988), and those that are both physical and geochemical in nature (e.g., Wilson, 1982; Lawrence and Hendy, 1985). Biological studies have resulted in the discovery of modern blue-green algal stromatolites in Antarctica, and discussion of the biological structures of the algal communities (Parker and others, 1981); observations of the geochemical and physical effects of the ice cover on the lake biota (Parker and others, 1981; Wharton and others, 1989), and, conversely, biotic effects on lake geochemistry (Wharton and others, 1987).

Much of the work done on Lake Hoare in particular is relatively recent. Studies have focused on climatological effects on ice thickness (Clow and others, 1988; Wharton and others, 1992), and the effects of the ice cover on the biology and sedimentary processes of the lake (Nedell and others, 1987; Squyres and others, 1991; Andersen and others, 1993). Clow and others (1988) used data from a newly established meteorological station to study the effects of the local climate on the Lake Hoare ice cover. With the data collected, they developed a model to determine the rate of ice sublimation from the lake. Wharton and others (1992) discussed how the changes in ice cover thickness and water levels of the dry valley lakes may reflect local to global climatic changes. Andersen and others (1993) discussed how sedimentation in the lakes may be cyclical due to ice-sediment interaction and/or climatic changes.

Squyres and others (1991) examined how highly localized sedimentation through the Lake Hoare ice cover is reflected in the sedimentary structures of the lake-bottom sediment. They suggested that distinctive sand mounds observed on the lake bottom are the primary sedimentary structures in the lake, and that variations in the sizes and shapes of these mounds are due to local variations in water depth and sedimentation rate. These mounds are described and analyzed here, along with other sedimentary structures

observed in the lake-bottom sediment, forming the main focus of this study.

PHYSICAL SETTING

The dry valleys were carved during an episode of continental glaciation that may have reached its peak in the middle Miocene or earlier (Brady, 1982). The most recent glaciation of the valleys ended less than 10,000 years ago, as indicated by the presence of non-marine diatom assemblages in deltas of glacial Lake Washburn, which occupied Taylor Valley from approximately 21,200 to 8,340 years ago (Kellogg and others, 1980).

The valleys are bounded by McMurdo Sound to the east and by the Transantarctic Mountains and the polar plateau to the west (Fig. 1). The Antarctic ice sheet covers the polar plateau; a small tongue of ice spills over the mountains and forms Taylor Glacier at the western end of Taylor Valley.

The floors of the valleys are mantled with moraines derived from the surrounding sedimentary, metamorphic and plutonic rocks. The Kukri Hills and the Asgard Range, which border Taylor Valley to the south and the north, respectively (Fig. 1), consist of upper Precambrian or lower Paleozoic Skelton Group metamorphic rocks, and plutons and dike swarms of the lower Paleozoic Admiralty Intrusives. Further inland lie cratonic sedimentary rocks of the Devonian (or older) to Jurassic Beacon Supergroup, which

is intruded by Jurassic Ferrar Dolerite (diabase) sheets and sills (McKelvey, 1982).

The ice-free nature of the dry valleys is primarily caused by the restriction of glacial flow from the polar plateau by the Transantarctic Mountains. In addition, precipitation (as snowfall) is low and local ablation rates of ice and snow from the dry valleys are relatively high. Clow and others (1988) established that the mean annual air temperature at Lake Hoare during 1986 was -17.3°C , with highs in the summer up to $+5^{\circ}\text{C}$ and winter lows down to -40°C . The wind speed, although highly variable, averaged 3.3 m/s.

Lake Hoare is located at the eastern end of Taylor Valley at $77^{\circ}33'\text{S}$, $162^{\circ}53'\text{E}$ (Fig. 1). Canada glacier dams it on its east end and separates it from Lake Fryxell to the east (Figs. 1, 2). Lake Hoare is 4.1 km long, is 1 km wide at its widest point, and has a mean depth of 14 m and a maximum depth of 34 m (Fig. 2).

Most of the sediment along the shoreline is coarse and poorly sorted, with boulders up to 50 cm in diameter (Nedell and others, 1987). Finer material (sand with minor pebbles and cobbles) occurs near meltstreams of Canada glacier. A sand bank 10-15 m wide, and about 50 m long and 5 m high lies at the east end of the lake, adjacent to the glacier. The sand bank, presumed to be eolian in origin because it is mostly well sorted sand, contains

a minor amount of cobbles that were sloughed off of the face of the glacier (Nedell and others, 1987).

Lake Hoare receives most of its water from the glacial meltstreams (Wharton and others, 1992). It may also receive minor amounts of water from Lake Chad to the west, from groundwater inflow near Canada glacier, and possibly from direct melting of the glacier where it is in contact with the lake water. The lake has no outflow streams; therefore, the only mechanisms by which it loses water are by ablation at the surface of the ice, and by evaporation from a 3- to 5-m-wide "moat" that forms on the margins of the lake during most austral summers (Squyres and others, 1991).

The temperature of Lake Hoare at the ice/water interface is 0°C. Freezing occurs at this interface and ablation occurs off the top of the ice cover, causing continuous upward migration of the ice. Simmons and others (1986) observed the migration rate to be approximately 1 m/yr.

The ice cover on Lake Hoare has thinned in the recent past from approximately 5.5 m thick in 1977 to approximately 3.3 m thick in the summer of 1987-88 (Wharton and others, 1989). The character of the ice cover also has changed in the recent past. During the summer of 1979-80 the surface of the ice was white, porous, and gently undulating. By the summer of 1984-85 the ice surface had become rugged, with ridges of friable ice 10-30 m wide and about 1 m high

extending approximately parallel to the long axis of the lake (Nedell and others, 1987). The ice ridges, referred to as ablation tables (Squyres and others, 1991) stand above 1- to 10-m-wide ice troughs. The ice in the troughs, which is hard and clear at the beginning of the summer, undergoes extensive surface melting during the peak of the summer (Wharton and others, 1992). Refreezing of the water in the troughs during the winter produces the hard, clear ice observed at the beginning of the next summer.

Clow and others (1988) estimated the ablation rate from Lake Hoare to be approximately 35 cm in 1986. Based on an upward migration rate of 1 m/yr and the ablation rate of only 35 cm/yr, Wharton and others (1992) concluded that the difference may be due to percolation of meltwater down through the ice, representing additional ice lost to melting, at a rate of approximately 65 cm/yr.

The ice cover prevents wind-generated mixing of the lake water. As a result, gases in the water column are perpetually stratified, and the water column is anoxic below 26 m (Wharton and others, 1987).

Boulders averaging approximately 1 m in size have been observed over much of the ice surface (Squyres and others, 1991). Several mechanisms have been suggested for the boulders getting onto the ice. Near Canada glacier, they may be deposited onto the ice by the glacier. Away from the glacier, they may roll onto the ice from steep

slopes bordering the lake. When intentionally rolled onto the rough summer ice cover, however, they did not move more than approximately 10 m onto the ice (Squyres and others, 1991). It is possible, therefore, that once they are on the ice cover, the boulders are rafted toward the center of the lake by lateral ice movement. Boulders may also be rafted toward the center of the lake after being plucked by the ice from submerged moraines in shallower areas of the lake. The boulders conceivably could melt through the ice cover and end up on the lake bottom, but all boulders on the ice are at the ice surface, and none have been reported from within the ice.

The glaciogenic nature of Lake Hoare is reflected in the undulating morainal bottom topography that also is displayed in the glacial moraines surrounding the lake (Squyres and others, 1991). Boulders observed on sloping portions of the lake bottom covered with a thin layer of fine-grained sediment probably represent clasts within the moraines that have not yet been covered by lacustrine sediment. Boulders have not been seen on relatively flat areas of the lake bottom; within areas with abundant lacustrine sediment, the rough topography is produced by localized sedimentation, which has produced many rounded to conical sand mounds up to a meter in height (Squyres and others, 1991).

According to Eyles and Miall (1984), proglacial lakes typically receive a large amount of sediment from meltwater conduits and subaqueous fans, with an additional component supplied by ice rafting. The resulting deposits include massive sediments deposited from suspension and from ice-rafted debris; sediment reworked by tractive currents and sediment-gravity flows; and deltaic deposits consisting of upward-coarsening, ripple-laminated, planar and trough cross-bedded sands. In contrast, recent sediments in Lake Hoare consist of interbedded algal mat layers and relatively coarse, discontinuous sand layers, including the sand mounds. Neither sediment-gravity-flow deposits nor evidence of tractive currents have been recognized in any of the cores (Squyres and others, 1991).

Work by Squyres and others (1991) suggests that the discontinuity of the sand layers is caused by highly variable sedimentation rates and localized sedimentation. The authors attempted stratigraphic correlation between nine sediment tube cores that were collected approximately 1.5 m apart in a 3x3 grid pattern on a relatively flat area of the lake bottom. Most of the sand layers could not be correlated, even between adjacent cores. Many of the algal mat layers, however, appeared to be relatively continuous and correlative. Nedell and others (1987) hypothesized that this is because the mats recolonize a sediment surface after sedimentation ceases. Squyres and

others (1991) suggested that the mats can recolonize a new sediment surface within a few years.

Analysis of sediment-trap data collected between December, 1982, and November, 1985, showed highly variable sedimentation rates between traps separated by only 1 to 2 m (Squyres and others, 1991). It was estimated from these data that the sedimentation rate was between 0.02 and 0.03 mm/yr near diveholes DH-1 and RH-2 and approximately 0.9 mm/yr at divehole GH-1 near the glacier (Fig. 2). Sedimentation rates may be higher near the glacier because of the amount of sediment available at the downwind end of the lake.

It was initially postulated that the mechanism by which sedimentation occurs in the lake is by sand working its way down through the ice cover. Nedell and others (1987) studied this process by comparing sediment trapped in the ice cover with that on the lake bottom. The similarity in texture and mineralogy between the two, along with the lack of other mechanisms of coarse sediment input into the lake, led them to the above conclusion. They and Wharton and others (1986) also showed, however, that the ice is too thick and cold for individual particles to pass through by melting the ice.

More in-depth, firsthand observation of the ice cover has produced conclusive evidence that the sand works its way down through the ice cover. The sand is initially

blown, or possibly rafted, onto the lake and then is trapped in local depressions in the ice. The trapped sand then absorbs solar radiation, raising the surface temperature of the particles above the melting point of the ice. Sand accumulates in the surficial meltwater ponds, typically 50 to 100 cm below the surface of the ice but meters above the base of the perennial ice cover. The sand then appears to work its way downward through the ice, perhaps through water-filled vertical fractures and gas-bubble columns (Fig. 3). Observations of these conduits from diveholes melted into the ice cover showed sand trapped in many of them (Squyres and others, 1991). One divehole was observed to be permeable to water below a depth of 2.1 m from the ice surface, and to contain no sand in the ice below 2.25 m from the surface. Evidently, the sand had been transported out of the ice and down into the lake. A schematic illustration of the ice cover is provided in Figure 4.

Nedell and others (1987), in an analysis of the sand, described it as moderately sorted and medium-grained, and classified it as submature lithic arkosic to feldspathic lithic sand. Both the material in the ice cover and the lake bottom sediment consists of these sands. The lake bottom sediment, however, contains a slightly larger percentage of very fine sand, silt and clay (fines). The lake bottom sediment contains 3.6% fines, versus 2.7% in

Figure 3. Gas bubble conduits in Lake Hoare ice cover (after Squyres and others, 1991). Horizontal scale equals vertical scale.

Figure 4. Schematic drawing of Lake Hoare ice cover and meltwater pools, indicating release of sand from the ice and mound formation. Mound height is vertically exaggerated.

the ice cover. Because of this difference, they theorized that some of the fines enter the lake in inflow streams and drift in suspension until they settle to the bottom.

The blue-green algae that grow on the lake bottom consist of three different morphologic types of mat communities at different depths in the lake (Parker and others, 1981). The depth distribution of each type is based on different environmental conditions, such as light, temperature, oxygen, nutrients, and salts (Parker and others, 1982). At the shallower depths of 5.5-11.0 m (0-6 m below the bottom of the ice), the accumulation of excess dissolved gases as bubbles causes lift-off of the mats, forming columnar mats or tearing mat pieces loose from the substrate. At depths >11 m, the mats remain stratiform and have internal laminae, and the accumulated thickness increases with depth. This is probably due to the lack of lift-off, because the pressure of accumulated oxygen inside the mats at these depths is not great enough to overcome the local hydrostatic pressure (Wharton and others, 1987).

The blue-green alga Phormidium frigidum Fritsch is the most abundant species present of all mat types in the lake (Parker and others, 1981). Pennate diatoms and heterotrophic bacteria also are present. These microorganisms thrive in this harsh environment because they are adapted to low light intensities, cold

temperatures, fresh to saline water, and anaerobic to oxygen-rich environments. In addition, the harsh lake-bottom environment inhibits the growth of competitive eukaryotes and burrowing or browsing metazoans.

Parker and others (1981) described the benthic algal mats as cold, freshwater stromatolites. The mats consist of preserved blue-green algal filaments and fine-grained, disseminated organic matter (Wharton and others, 1982). The mats also contain incorporated sediment and biogenic calcite. Clastic silicates and authigenic sulfide minerals are incorporated into the laminae of the anaerobic mats. In addition to the mats, much of the organic material on the lake bottom is disseminated interstitial unidentified matter (Squyres and others, 1991).

Blue-green algae are found in other modern environments, but the localized, mounded clastic sediment at the bottom of Lake Hoare may be unique to perennially ice-covered lakes. A detailed analysis of these unique sediments, as observed in sediment cores recently recovered from the lake bottom, is provided in the next section.

DESCRIPTION OF CORES

Methods

Seven sediment box cores were analyzed for this study. The cores were recovered from the bottom of Lake Hoare by scuba divers in November 1987. Access to the lake bottom was through three diveholes that were melted through the ice cover. The locations of the diveholes are shown in Figure 2. Table 1 outlines general information about the diveholes and the cores recovered from below them, including descriptions of the lake bottom that were provided by the divers.

Sample locations were selected to reflect potential differences in rates and mechanisms of sedimentation. Cores A and B were recovered near divehole DH-1, approximately 50 m south of the northern lakeshore, at a depth of 7-8 m. Cores C and D were recovered near divehole GH-1, approximately 50 m west of Canada Glacier and 500 m south of the northern lakeshore, at a depth of about 24 m. Cores F, G, and H were recovered near divehole RH-2, approximately 300 m south of the northern lakeshore and 750 m west of Canada Glacier, at a depth of about 25-30 m.

Water depths used in this study are approximate depths below the bottom of the ice. The depths from which Cores A and B were recovered were estimated from the

TABLE 1. LOCATIONS OF CORE SITES.

DIVEHOLE	CORE	DEPTH BELOW ICE COVER (M)	LOCATION DESCRIPTION	SAMPLE LOCATION DESCRIPTION
DH-1	A	7	Shallow	Edge of new(?) mound 15 x 80 cm, radial sample
DH-1	B	8	Shallow	Broad depression, 20 x 150 cm, luxurious mat
GH-1	C	24	Deep, near glacier	Mounds everywhere, many composite, from 10 cm to 1 m high; algae on all sfcs. Core C from crest of mound 80 cm high with light algal coating. Core D from side of mound 30 cm high, with thicker algal coating.
GH-1	D	24	Deep, near glacier	
RH-2	F	28	Deep, offshore	Lake bottom rough, with large, angular rocks. Open, slope.
RH-2	G	30	Deep, offshore	Smooth lake bottom beneath anaerobic zone.
RH-2	H	25	Deep, offshore	Lake bottom rough, with large, angular rocks with thin (1-2 cm) mat cover; sample from sandy area between rocks.

location of divehole DH-1 in relation to the lake bathymetry. The depths from which the remaining cores were recovered were approximated using the piezometric water depths measured by the divers with a depth gauge. Because the piezometric surface is located within the ice cover, the measured depths were adjusted by this author to be depths below the bottom of the ice. According to Wharton and others (1992), the depth of the bottom of the ice below the piezometric surface is roughly 0.9 times the ice thickness, which in 1987 was 3.3 m. Therefore, the bottom of the ice was approximately 3 m below the piezometric surface. In addition, the depth gauge was calibrated to the density of seawater. Because Lake Hoare contains fresh water (Parker and others, 1982), measured depths were also adjusted for the difference in density between the two types of water.

The cores were made by a method similar to that described by Bouma (1969). Metal core boxes 20 cm x 15 cm x 7-1/2 cm in size were used. Each box consisted of an open-ended base with four sides and an attached cover; a separate steel plate was used as the bottom. The box was first pushed vertically into the sediment, then the sediment was dug away from one side of the box, the steel plate was inserted under the open end of the box and held in place with rubber tubing, and the box was removed.

Epoxy peels of the cores were made by the divers in the field while the cores were still wet in order to preserve the sedimentary structures of the cores for analysis. The cores were then hand-sketched, described, and analyzed in the laboratory by this author. The sedimentary structures in the cores were observed "in situ" because the sediment in peels is epoxied in place; however, although the epoxy preserves the sedimentary structures, it prevents sieving the sediment. Grain sizes, grain size classes, and sorting were therefore visually estimated using Compton's (1985) methods for describing rocks in the field.

Photographs and sketches of the cores are provided in Figures 5-16. Detailed descriptions of the cores are provided in the Appendix. For purposes of analysis, each core was divided into convenient descriptive units that may or may not correspond with depositional units.

The overall shape of each sand unit is described as being either uniform in thickness, wedge-shaped, or lens- or mound-shaped. These shapes are illustrated in the explanation of the core descriptions in the Appendix. A unit that is uniform in thickness has subparallel upper and lower boundaries, a wedge-shaped unit has roughly planar boundaries that are not parallel. A lens- or mound-shaped unit pinches out and typically has a curved upper boundary.

Figure 5. Photograph of Core A, from Divehole DH-1 at a depth of 7-8 m. Microbial mats are visible in middle of core. Tape (folded back) at top designates top of core. Core is 14 cm wide.

EXPLANATION

- SAND AND A PEBBLE
- STRATIFORM ALGAL MATS
- DISCONTINUOUS, CURLED ALGAL MATS
- DESCRIPTIVE UNIT

Figure 6. Core A, from Divehole DH-1 at a depth of 7-8 m.

Figure 7. Photograph of Core B, from Divehole DH-1 at a depth of 7-8 m. Microbial mats are visible in upper portion of core. Scale is in centimeters.

Figure 8. Core B, from Divehole DH-1 at a depth of 7-8 m. Refer to Figure 6 for explanation.

Figure 9. Photograph of Core C, from Divehole GH-1 at a depth of 24 m. Tape designates top of core. Core is 14 cm wide.

Figure 10. Core C, from Divehole GH-1 at a depth of 24 m. Refer to Figure 6 for explanation.

Figure 11. Photograph of Core D, from Divehole GH-1 at a depth of 24 m. Mounded units are visible at left. Area at upper right disturbed during sampling. Tape designates top of core. Scale is in centimeters.

Figure 12. Core D, from Divehole GH-1 at a depth of 24 m. Blank area in upper right corner was disturbed during sampling. Refer to Figure 6 for explanation.

Figure 13. Core F, from Divehole RH-2 at a depth of 25-30 m. Refer to Figure 6 for explanation.

Figure 14. Photograph of Cores H (on left) and G, from Divehole RH-2 at a depth of 25-30 m. Tape designates top of Core H. Top of Core G is at top of ruler (material above used for packing the core). Scale is in centimeters and inches.

Figure 15. Core G, from Divehole RH-2 at a depth of 25-30 m. Refer to Figure 6 for explanation.

Figure 16. Core H, from Divehole RH-2 at a depth of 25-30 m. Refer to Figure 6 for explanation.

Microbial mats are described as either stratiform or detrital; a stratiform mat is layered and appears to be in place, whereas a detrital mat consists of mat fragments that appear to have been re-worked. A stratiform mat with intact layering is described as continuous, and that without intact layering is described as discontinuous.

The relative abundance of a component or feature is described as "rare" if it comprises less than 2% of a unit, or as "sparse" if it comprises from 2-10% of a unit. A component with a relative abundance of more than 10% is included in the sediment description. Sand that contains much disseminated organic matter that is not mat is described as "organic-rich". It is difficult to see all of the sand, particularly all of the sand grain sizes, in organic-rich sand and in sandy mat layers; therefore, the grain size descriptions of these units are the best that can be estimated from visual observation of the impregnated cores.

Units in the cores are described as normally graded if they fine either upward, or upward and outward. As will be discussed in the interpretation, fining upward and outward may be the form normal grading takes in units deposited rapidly from localized sources. In some units that fine upward and outward, only portions of the units were recovered in the cores.

Results

The cores consist of interbedded sand and mat units of varying thickness and lateral extent. As indicated by Nedell and others (1987), the sediment is submature lithic arkosic to feldspathic lithic sand, which is reflected in the abundant light-colored grains. All of the cores except Cores C and D are, in general, medium greenish-gray due to the presence of the blue-green algae. Core C, which is topped with very little mat, and Core D, which contains no recognizable mats (Fig. 12), consist of finer grains that are mostly dark green to black and coarser grains that are white to pink. Other variations in color, where present, are discussed in the core descriptions.

In general, the fine- and medium-sized grains are subangular to subrounded, and the coarse and very coarse grains are subrounded to rounded. These observations of rounding of grains were visually estimated, not statistically analyzed.

The cores were grouped together for description based on similarities in their recovery (i.e., divehole) locations. Cores A and B are considered nearshore and shallow; Cores C and D near-glacier (near Canada Glacier) and deep; and Cores F, G, and H, offshore and deep.

Nearshore, Shallow Cores

Cores A and B were recovered from near divehole DH-1 (Fig. 2) at a depth of 7-8 m. Core A (Fig. 6) was recovered as a radial section from a mound that had been deposited since the previous field season. The mound was about 15 cm in height by 80 cm in diameter. The core consists of a lower sandy, organic-rich portion and an upper, sandy, wedge-shaped portion. The length of the core is 130 mm on one side of the core and 150 mm on the other side.

The core consists of four units (Fig. 6), the lower three of which slope toward the crest of the mound from which the core was recovered (toward the left). Unit 1, the lowermost unit, is 0-20 mm thick and is truncated at the bottom of the core. The sand is moderately sorted, fine- to coarse-grained, and contains a curled clump of organic matter near the top of the unit. The unit contains interbedded mats that consist mostly of discontinuous, curled pieces several layers thick and up to 15 mm long, except at the top, where they are sub-stratiform and discontinuous and contain some carbonate crystals. This could be detrital mat material or a mat layer that was disturbed during sampling. The sand/mat ratio of this unit is approximately 2:1.

Unit 2 consists of 10-35 mm of moderately sorted, fine- to coarse-grained sand with rare very coarse grains.

A laterally discontinuous cluster of medium to very coarse grains is at the lower right of the unit.

Unit 3 consists of 35-55 mm of interbedded organic-rich sand and sandy mat layers. The sand is moderately sorted, and fine to coarse grained, except for a well-sorted, fine-to medium-grained cluster at the left center. In the upper 2-3 mm the mat layers are stratiform and continuous. Below the continuous mat layers, the mats are stratiform, discontinuous and wavy, and define a weak stratification. The sand/mat ratio of this unit is approximately 10:1.

The upper unit, Unit 4, is wedge-shaped and ranges from approximately 30 mm thick on the right to approximately 85 mm thick on the left. The unit consists of sand that is well sorted, indistinctly stratified, and normally graded near the base to homogeneous near the top. The sand is fine to medium grained at the base and on the left side and grades upward to very fine to fine grained at the top and on the right side. The unit contains sparse very thin pieces of detrital mat 2-3 mm long. The mat pieces are oriented subparallel to each other and define a weak stratification. At the base of the unit, the stratification is oriented subparallel to the lower boundary of the unit, which slopes toward the left. Higher up in the unit, the stratification becomes oriented subhorizontally, then begins to slope toward the right at the top of the unit, subparallel to the upper boundary

of the unit. The sand/mat ratio of the unit is approximately 50:1.

Core B (Fig. 8) was recovered from a broad depression, roughly 20 by 150 cm in size, that was covered with algae. The core, with a total length of 100-120 mm, consists of two units. The lower unit consists of 85-100 mm of indistinctly stratified, moderately sorted, fine- to very coarse-grained sand with a few finer- and coarser-grained clumps. The sand is organic-rich in the upper 15-20 mm and in clumps below.

The upper unit of Core B consists of 15-20 mm of discontinuous and wavy, randomly oriented, sandy mat material. The sand is medium to very coarse grained. The sand/mat ratio of the unit is approximately 1:4.

Near-glacier, Deep Cores

Cores C and D were recovered from near divehole GH-1 (Fig. 2) at a depth of approximately 24 meters. The diver observed many sediment mounds in this area (David Andersen, pers. comm., 1993). The mounds ranged from approximately 10 cm to 1 m high, and many were composite mounds. Algae thinly covered the surface of the entire area.

Core C (Fig. 10) was recovered from the crest of a mound approximately 80 cm high with a light algal coating. The core is approximately 150 mm long and consists almost entirely of sand.

Unit 1 at the base of Core C is normally graded and consists of very well-sorted, fine-grained sand that grades upward to very fine- to fine-grained sand. The unit is uniform in thickness and is approximately 25 mm thick. It contains three interbeds on the left side consisting of pinch-out edges of lens- or mound-shaped units of moderately sorted, medium- to coarse-grained to poorly sorted, fine- to very coarse-grained sand.

Unit 2 is uniform in thickness and inversely to normally graded. It consists of poorly sorted, fine- to coarse-grained sand with sparse very coarse grains at the base; well-sorted, medium- to very coarse-grained sand in the middle; and poorly sorted, fine- to coarse- grained sand with sparse very coarse grains at the top. The unit is approximately 35 mm thick.

Unit 3 is similar to Unit 1, consisting of well-sorted, fine-grained sand with rare medium to coarse grains, and an interbedded pinch-out edge of a lens- or mound-shaped unit of well-sorted, medium- to coarse-grained sand on the left side. The unit is approximately 15 mm thick. In contrast to the large mound of Unit 4 of Core A, the lens- or mound-shaped units within Units 1 and 3 of Core C are relatively thin, the upper and lower boundaries are at a low angle to subparallel, and they pinch out over a relatively long distance. No grading was observed in them, and the coarse grains are distributed relatively

evenly throughout the units. The pinch-out edges of the units are 3-5 medium-sized sand grains thick.

Unit 4 is uniform in thickness and approximately 10 mm thick. It is normally graded and consists of sand that is moderately sorted, fine to coarse grained on the left to well sorted, fine to medium grained on the right.

Unit 5 consists of moderately sorted, fine- to coarse-grained sand, and is a portion of a lens- or mound-shaped unit. The unit is 0-12 mm thick. The external geometry of this unit is noticeably different from the lens- or mound-shaped units within Units 1 and 3. The upper boundary of Unit 5 is curved slightly, convex upward, and the unit is thicker and pinches out over a much shorter distance.

Units 6 and 7 are normally graded like Unit 4, and, along with Unit 8, uniform in thickness and curved, convex upward. Unit 6, which is approximately 15 mm thick, consists of sand that is well sorted, medium to coarse grained on the left to very well sorted, medium grained on the right. Unit 7, which is approximately 10 mm thick, consists of sand that is well sorted, fine to medium grained on the left to well sorted, medium to coarse grained on the right. Unit 8, which is approximately 35 mm thick, consists of sand that is very well sorted, very fine to fine grained, with 2 interbedded very thin mat layers at the top.

Core D (Fig. 12) was recovered from the side of a mound approximately 30 cm high. The diver claimed that this mound had a thicker algal coating than that of Core C (David Andersen, pers. comm., 1993). The core, which is 140-160 mm long, fines upward and consists entirely of interbedded finer- and coarser-grained sand units that slope toward the left. No mat layers were observed at the top of this core.

Units 1, 3, 5, 7, 9, and 11 consist of well-sorted, fine- to medium-grained sand with sparse coarse to very coarse grains. The units are uniform in thickness, and none are graded. Units 3 and 5 coalesce to the left. Units 1, 3, and 9 are approximately 4 mm thick. Units 5 and 7 are approximately 3 mm thick. Unit 11 is approximately 10 mm thick.

Units 2, 4, 6, and 8 consist of well-sorted, coarse- to very coarse-grained sand. Units 2, 4, and 6 appear to be portions of lens- or mound-shaped units that pinch out toward the left side of the core. Unit 2 is 1-8 mm thick, Unit 4 is 0-5 mm thick, and Unit 6 is 3-10 mm thick. Unit 8 is uniform in thickness, but, because of its coarse grain size, probably also is a portion of a lens- or mound-shaped unit, the pinch-out edges of which were not recovered in the core. Unit 8 is approximately 15 mm thick. None of these units is graded.

Unit 10 consists of moderately sorted, medium- to very coarse-grained sand, with rare very fine- to fine-grained, flat-pebble gravel. The unit is uniform in thickness, and is approximately 13 mm thick. Similar to Unit 8, Unit 10, although uniform in thickness, is coarse-grained and may also be a portion of a lens- or mound-shaped unit, the pinch-out edges of which were not recovered in the core. This unit is also not graded.

Unit 12 is normally graded and consists of moderately sorted, fine- to coarse-grained sand with sparse very coarse grains at the base and the middle of the right side, to well-sorted, very fine- to fine-grained sand with rare coarse to very coarse grains on the left side and at the top. Although the unit is uniform in thickness, it may also actually be a portion of a lens- or mound-shaped unit, the pinch-out ends of which were not recovered in the core. The unit is approximately 35 mm thick.

Unit 13 consists of moderately sorted, fine- to very coarse-grained sand that is not graded. The unit is uniform in thickness and is approximately 10 mm thick. Similar to the other coarse-grained Units 8 and 10, Unit 13, although uniform in thickness, may also be a portion of a lens- or mound-shaped unit.

Unit 14 consists of very well-sorted, very fine-grained sand that is not graded. The unit is uniform in thickness and is approximately 3 mm thick.

Unit 15 consists of well-sorted, fine-grained sand with some coarse grains. The unit is wedge-shaped and is approximately 8-18 mm thick. This unit may be wedge-shaped because it was recovered from the flank of a mound. It is also not graded.

Offshore, Deep Cores

Cores F, G and H were recovered from near divehole RH-2 at a water depth of 25-30 m. The lake bottom below the divehole was described by the divers as rough, rocky, and locally steep, with a covering of algae (David Andersen, pers. comm., 1993). Core F was recovered from an open slope; Core G was recovered on the lake bottom in the anaerobic zone, approximately 1 m below a widespread chemocline (Wharton and others, 1987); and Core H was recovered on a slope above the chemocline in an area with a thin coating of algae.

Core F (Fig. 13) is approximately 90 mm long. The core is sandier in the bottom half than in the top half, and the sand units are bounded by thin mat layers. Unit 1 is mound-shaped and normally graded. It consists of moderately-sorted, fine- to coarse-grained sand in the center, grading to well-sorted, fine- to medium-grained, organic-rich sand on the sides. The unit is 3-15 mm thick and is topped with a very thin mat layer. Unit 2 is mounded and also normally graded, except at the base, where it

consists of a very thin layer of well-sorted, fine- to medium-grained sand. The remainder of the unit consists of sand that is well sorted and fine to medium grained at the left, where the unit thins over the underlying unit, to well sorted, medium to coarse grained at the right, where the unit is thickest. The unit is 2-14 mm thick and is topped with a very thin mat layer.

Units 3 and 5, which are uniform in thickness and curved, convex upward, and Unit 4, which is mound-shaped, show no grading. Unit 3 consists of moderately sorted, fine- to coarse-grained sand that thins both to the left and right over the underlying mounded units. Unit 4 consists of well-sorted, fine- to medium-grained sand with rare coarse grains. It is topped with sand that has a yellowish-orange discoloration, is 2-5 mm thick, and thins similar to Unit 3 over the underlying mounded units. Unit 5 consists of moderately sorted, fine- to coarse-grained sand that contains a minor amount of disseminated organic material. The unit is approximately 15 mm thick. The upper and lower boundaries are curved, convex upward.

Unit 6, which is uniform in thickness and curved, convex upward, is normally graded. It consists of sand that is well sorted and medium to coarse grained with rare very coarse grains at the base, to well sorted, fine to medium grained at the top. The unit is approximately 3 mm thick.

With the exception of Unit 4, each of these six units is topped by a very thin mat layer. The overall sand/mat ratio of Units 1-6 is approximately 25:1.

Units 7 and 8 consist of interbedded thin sand units that are uniform in thickness and curved, convex upward, and very thin mat layers. They are transitional between the lower, sandy units and the upper, organic-rich sand and thicker mat units. The sand of Unit 7 is moderately sorted, and fine to medium grained with sparse coarse grains. The sand of Unit 8 is well sorted and fine grained. Unit 7 is approximately 3 mm thick and Unit 8 is about 1 mm thick; neither of the units is graded. The sand/mat ratios in Units 7 and 8 are approximately 10:1 and 5:1, respectively.

The upper units, Units 9 through 13, consist of sand layers, none of which are graded, interbedded with sandy mat layers. All of the sand layers are uniform in thickness and curved, convex upward. The sand layers contain moderately sorted, fine- to very coarse-grained sand, and well sorted, medium- to coarse-grained sand. Two of the sand units, Units 10 and 12, are relatively thick (3-5 mm). One of the sand layers within Unit 9 is also relatively thick (3 mm). It consists of well sorted, medium- to coarse-grained sand, and it is only a few grains thick. The sand in the sandy mat layers is moderately sorted and fine to coarse grained. The mat layers are

stratiform, continuous, and curved, convex upward, similar to the sand layers. The overall sand/mat ratio of Units 9-13 is approximately 2:3.

Core G (Fig. 15) is approximately 150 mm long. The wedge of sand at the bottom right of Unit 1 of Core G is blackish-brown. The upper, mat-rich portion of Core G is dark grayish-green, and Core G is greener overall in color than any of the other cores.

Unit 1 of Core G consists of 85-87 mm of interbedded organic-rich sand and mat layers. The sand is wedge-shaped at the base of the unit, possibly because of truncation at the base of the core, and is moderately sorted, fine to coarse grained, with sparse very coarse grains. The sand is not graded. The mat layers are sub-stratiform, very thin, and discontinuous, and slope toward the left. The sand/mat ratio in this unit ranges from approximately 15:1 at the base of the unit to approximately 3:1 in the middle of the unit to approximately 4:1 at the top of the unit.

Unit 2 of Core G consists of interbedded organic-rich sand and mat layers. The sand is moderately sorted, and fine to coarse grained. The mat layers are very thin and stratiform. There are 5-6 sand layers and 4-5 mat layers.

The middle of Core G - Units 3, 4, and 5 - consists of organic-rich sand units and very little mat. Unit 3 consists of normally-graded, organic-rich, fine- to

medium-grained sand. The unit is uniform in thickness and approximately 4 mm thick. Although the top of Unit 3 is not bounded by mat layers, the boundary between Units 3 and 4 is very sharp. Unit 4 is a small lenticular unit that is 2-6 mm thick and is normally graded. It consists of moderately sorted sand that is medium to very coarse grained in the center to medium to coarse grained on the sides. The unit is topped with a very thin mat layer; the sand/mat ratio of the unit is approximately 7:1. Unit 5 is wedge-shaped. It is approximately 10 mm thick at the right side of the core and pinches out near the left side of the core. It consists of organic-rich sand that is normally graded. The sand is moderately sorted, fine to coarse grained on the right where the wedge is thickest, and well sorted, fine to medium grained at the top and the left side of the unit.

Unit 6 consists of organic-rich sand that is well sorted and fine to medium grained with rare very coarse grains. The unit is uniform in thickness except where it thickens at the left over the thinner side of the underlying wedge-shaped unit. The unit is not graded.

The upper unit of Core G, Unit 7, consists of interbedded sand and sandy mat layers. The sand layers are uniform in thickness. The sand layers are organic-rich and the sand is well sorted, fine to medium grained to moderately sorted, medium to very coarse grained. The

sand in the sandy mat layers is moderately sorted and fine to coarse grained. The mat layers are stratiform and continuous. The sand/sandy mat ratio of the unit is approximately 2:1.

Core H (Fig. 16) is approximately 120 mm long. Unit 1 of Core H is 15-55 mm thick, and consists of a wedge of organic-rich sand 3-30 mm thick at the base, overlain by 10-25 mm of interbedded sand and mat layers. The sand is moderately sorted and fine to coarse grained, with rare very coarse grains. The sand is not graded. The mat layers are very thin, sub-stratiform to discontinuous, and slope toward the left. The sand/mat ratio of this unit is approximately 20:1.

Unit 2 consists of 0 to 45 mm of moderately sorted, fine- to coarse-grained sand. The unit is wedge-shaped, and it pinches out toward the right. The unit is not graded. The sand/mat ratio of this unit is approximately 25:1. Two mat layers thinly interbedded with sand top both Units 1 and 2.

The middle of Core H - Units 3-6 - consists of organic-rich sand units and some mat layers. Unit 3 is a portion of a lens- or mound-shaped unit on the left side of the core. At the left it is approximately 7 mm thick, and it pinches out to the right. It consists of well-sorted, fine-grained sand with rare medium to coarse grains. The sand is not graded. The unit is topped with a very

thin mat layer; the sand/mat ratio of the unit is approximately 20:1.

Unit 4 is a portion of a lens- or mound-shaped unit on the right side of the core. At the right it is approximately 15 mm thick, and it pinches out to the left. It consists of moderately sorted, fine- to coarse-grained sand that is not graded. The unit is topped with a very thin mat layer; the sand/mat ratio of the unit is approximately 20:1.

Unit 5 consists of interbedded sand and mat layers. There are approximately 5 sand layers and 5 mat layers. The sand layers are uniform in thickness and toward the right are curved over Units 3 and 4. The thickness of the unit is approximately 5 mm at the left to approximately 10 mm at the right. The sand is organic-rich, and is moderately sorted, very fine to medium grained to fine to coarse grained. The sand is not graded. The mat layers are stratiform and continuous. There is a very thin layer of calcium carbonate crystals at the top of the unit. The sand/mat ratio of the unit is approximately 10:1.

Unit 6 consists of well-sorted, normally-graded sand that is uniform in thickness and approximately 10 mm thick. The sand is medium-grained in the bottom approximately 10 mm, and fine- to medium-grained in the top approximately 2 mm.

The upper portion of Core H consists of interbedded sand and sandy mat units. Unit 7 consists of approximately 35 mm of thinly interbedded organic-rich sand and sandy mat layers. The sand in the sand layers is uniform in thickness, and very well sorted, medium grained to moderately sorted, medium to coarse grained. The sand in the sandy mat layers is moderately sorted, fine to coarse grained, with one subangular pebble. The sandy mat layers are substratiform and continuous. The sand to sandy mat ratio of the unit is approximately 1:1.

Unit 8 consists of approximately 3 mm of sand that is uniform in thickness. The sand contains a minor amount of disseminated organic matter, and is well sorted and medium grained. Unit 9 consists of approximately 2 mm of sandy mat layers that are similar to the sandy mat layers of Unit 7. The mat layers are substratiform and continuous, with moderately sorted fine- to coarse-grained sand.

INTERPRETATION

The cores apparently reflect extreme temporal and spatial variability of sedimentation in Lake Hoare, as indicated in the wide range of sedimentary structures and sequences described in the previous section. No consistent vertical sequences are recognized in the cores, and these short cores do not seem to record any recognizable signal of lakewide changes during the interval that they represent. The character of the lake-bottom sediment, specifically the shape of the sand and mat layers, and the sorting and grading of the sand, suggests that constraints on mechanisms of sedimentation occurring in the lake can be interpreted.

Sedimentary Structures

Mounded Sand

Recent sedimentation rates vary in different settings in the lake (Squyres and others, 1991). These differences in sedimentation rates, as well as variations in water depth, may cause variations in sedimentary structures. Mounded sand units, for instance, differ structurally in different parts of the lake. The mounded units of Cores F, G, and H from divehole RH-2, where sedimentation is slow, are broad and relatively flat. The mounded units of Cores C and D from divehole GH-1, where sedimentation rates have been measured to be 1-2 orders of magnitude

greater than at divehole RH-2 (Squyres and others, 1991), are steeper and distinctly stratified. The upper wedge-shaped unit of Core A, which apparently was deposited even more rapidly, is steep, but is barely visibly stratified.

Core A is the only nearshore, shallow core that contains a wedge- or mound-shaped unit, and that is Unit 4. Unit 4 is wedge-shaped, relatively thick, normally graded, and displays weak internal stratification.

Core A was recovered from what probably was a new mound that the divers did not observe the previous field season. Unit 4 of Core A represents the new mound and must have been deposited rapidly enough to form between one summer and the next. The sandy mats of Unit 3 of Core A, which underlies the wedge-shaped unit, and the sandy mats of Unit 2 at the top of Core B, are inferred to be the same mat unit because the mats were observed to be covering the entire lake bottom below divehole DH-1 before the new mound formed. Unit 4 of Core A is only weakly stratified. The relatively homogeneous sand grain size of the unit does not show stratification, which is defined by the orientation of detrital mat pieces. The weakness of the layering and the gradual change in orientation of the layering suggest that the unit was deposited by a relatively continuous release of sand from the ice.

Divehole RH-2 is offshore and deep, and it has a recent sedimentation rate similar to that of divehole DH-1 (Nedell and others, 1987). The wedge- or mound-shaped units from this divehole include Units 1, 2 and 4 of Core F; Units 4 and 5 of Core G; and Units 3 and 4 of Core H. All of these units are approximately 5-6 times thinner than Unit 4 of Core A, and the mound-shaped units are closer to a classic Gaussian shape, with gently curved upper boundaries. The wedges of sand at the bases of Unit 1 of Core G and Unit 1 of Core H do not resemble these smaller wedge- or mound-shaped units, and they may be portions of tabular units that were truncated during the coring process.

The structures of these units, although they are all from the areas of relatively slow average sedimentation, differ between the two diveholes; however, they all have surface slopes up to 20° that generally reflect the reported external geometry of the mounds. Mounds near divehole DH-2 have been observed to be up to 1 m in diameter and up to 20 cm in height, with typical surface slopes of approximately 20° (Squyres and others, 1991). Divehole DH-2 is approximately 100 m from divehole DH-1 (Fig. 2) and has a recent sedimentation rate similar to that of diveholes DH-1 and RH-2 (Nedell and others, 1987).

Cores C and D were recovered from near divehole GH-1. The mounds near divehole GH-1 have been observed

to be up to 1 m in height, are conical with sharp peaks, and some have flanks that are at the angle of repose (Squyres and others, 1991). The mounded units of Core C, however, do not reflect the sharp-peaked geometry that was observed at the crest of these mounds. The only units in Core C that are obviously mounded are the relatively thin, flat-lying, interbedded, pinch-out layers within Units 1 and 3, and Unit 5, near the bottom of the core. Units 4, 6, 7, and 8, however, which appear to be uniform in thickness, and the latter three of which are curved, convex upward, could be the crests of mounded units, the steeper, pinch-out edges of which were not recovered in the core. If Core C does consist of interbedded crests and flanks of mounded units, then it suggests that mounds are composites of multiple mounded units.

Core D, which was recovered from the flank of a mound, contains mounded units that do not slope near the angle of repose. There also is no evidence from the layer structure, such as inverse grading of sand-flow toes, that these were originally at the angle of repose and slid before sampling. Why the mounded units of these two cores do not reflect the external geometry of the mounds is a question that remains to be answered.

The attitude of the layers in Core D also is enigmatic. The layers appear to slope toward the crest of the mound from which the core was recovered, contrary to what would

be expected based on the external mound geometry, and Units 2, 4, and 6 pinch out toward the left. Unless the attitude is an artifact produced by disturbance during sampling, the core must have been recovered from a composite mound in which the sloping layers represent the opposite side of a mound that has been covered by the current mound (Fig. 17).

Squyres and others (1991) developed a numerical model for formation of small mounds at locations like those of diveholes DH-1, DH-2, and RH-2, and of the much larger mounds near divehole GH-1. The model mound based on the slow sedimentation rate at divehole DH-2 was small and nearly Gaussian-shaped. The model mound based on the faster sedimentation rate at divehole GH-1 was large and conical and had slopes at the angle of repose. Their model suggests that the differences in the morphology and shapes of the mounds can be attributed to differences in the sedimentation rates and mound sizes at the two different divehole locations.

Cores F, G, and H are from a deep divehole with a slower sedimentation rate, and their mound-shaped units resemble those of the model with the slower sedimentation rate. The mound-shaped Unit 5 of Core C, and Units 4, 6, 7, and 8 of Core C, which may be portions of mounded units, along with the mounded units of Core D, are from a deep divehole with a faster sedimentation rate, and all

Figure 17. Possible area of recovery of Core D from a composite mound; steepness exaggerated for clarity.

resemble the more flat-lying layers in the lower portion of the model with the more rapid sedimentation rate. The relatively thick wedge shape of Unit 4 of Core A, however, does not resemble any of the results of the numerical model.

The mounded units of the deeper cores with a slower sedimentation rate fit the model for mounds with slower sedimentation rates, and those from the cores with higher sedimentation rates fit that model. Water depth, therefore, may not be as significant in defining the shapes of the mounds as the rate of deposition. The model does not take into account, however, interruption of mound-forming processes by the non-mounded layers described below.

Non-mounded Sand

Although mounds are a common feature on the lake bottom, mounded or wedge-shaped units are not as prevalent in the cores as would be expected based on observations of the lake bottom. Instead, units that are uniform in thickness predominate. These units are concentrated in the lower portions of Cores A, B, and C, and in the upper portions of Cores F, G, and H. Specifically, they are Units 1, 2 and 3 of Core A, and Units 1 and 2 of Core B, all of which are relatively thick; most of Units 1-4 of Core C, with the exception of the interbedded pinch-out

edges of lens- or mound-shaped layers within Units 1 and 3; and all of the sand units that are interbedded with mat layers in the middle and upper portions of Cores F, G, and H.

These non-mounded units could be portions of thin, broad mounds, the pinch-out edges of which were not recovered in the cores because the cores are too narrow to show the layer geometry. They also could be sand units that were originally mound-shaped and were subsequently reworked by weak currents after deposition into non-mounded layers. Alternatively, these units could represent a scattering of grains from multiple sources in the ice, although the scattering probably would be over a limited area because the layers evidently do not extend from one core to the next. It is difficult to believe, however, that sediment released from different sources, although in the same area of the ice cover, would be of similar grain sizes and degree of sorting. Perhaps all of these mechanisms are involved. Another possibility, if these units are indeed portions of mounds, is that they are evidence that weak currents do occur in the lake, acting to scatter some of the sand as it falls through the water column into very broad mounds or non-mounded layers.

Microbial Mats

Mats in Lake Hoare display variations in structure

that can be attributed directly to variations in water depth and clastic sedimentation rates. Most of the mats in Cores A and B, for example, were affected by gas lift-off because they grew in shallow water; all of the mat material in most of Unit 3 of Core A and in Unit 2 of Core B is wavy and much is composed of fragments interpreted as redeposited pieces of lift-off mats. As the upper, continuous mats of Unit 3 in Core A show, however, not all mats in shallow areas are subject to lift-off. This may be because these mats were covered by the upper wedge of sand soon enough after they grew that gases did not have time to accumulate and lift-off did not occur.

Rapid clastic sedimentation may prevent mat growth or the accumulation of detrital mat material almost entirely. At divehole GH-1, rapid sedimentation has prevented the accumulation of mats in Cores C and D except at the very top of Core C, where some very thin mats have accumulated.

In contrast, the mats in the upper portions of Cores F, G, and H are relatively thick, stratiform and continuous. The thick mats were allowed to accumulate without much interruption because of the slower rates of sedimentation through the ice. In Cores F and H, benthic mats accumulated on the lake bottom. Beneath the anaerobic zone, however, from which Core G was recovered, mats did not grow; instead, the mats in the upper portion of

Core G may be detrital. It is also possible that these mats are relict benthic mats from a time when there was no anaerobic zone in that area of the lake. The mats in these three cores are stratiform and continuous, reflecting the fact that lift-off does not occur in deeper parts of the lake (Parker and others, 1981, 1982).

Sandy mats were observed in the upper units of Cores A, B, F, G, and H. The sand generally appears to be moderately sorted and fine to coarse grained or medium to very coarse grained. The presence of sand in the mats suggests that sedimentation through the ice may be occurring, although probably at relatively slow rates, even while mats are accumulating. Alternatively, perhaps the sand was scattered by currents from a nearby mound. Because it is so coarse, the sand was most likely not carried into the lake in suspension.

Sedimentary Processes

The variations in the sedimentary structures of the sand in Lake Hoare may or may not be caused by differences in depths of deposition, and they most likely are caused at least in part by different sedimentation rates. The differences also appear to be due to how the sediment is released from the ice. Mounded or wedge-shaped units probably were deposited from localized sources in the ice, and units that are uniform in thickness may have been

deposited by a scattering of grains from multiple sources in the ice or from the lake margins.

The sand may also be sorted or graded before, during, or after deposition. As will be shown, sorting and grading may occur on top of the ice, within the ice, or during release of sand from the ice. Sorting and grading could also occur during avalanching of sand down mound slopes after deposition on the lake bottom.

Sorting

The sand in the cores ranges from moderately sorted to very well sorted. Sorting of the sand may be caused by several different mechanisms. Eolian transport of the sand onto the ice causes the initial sorting, where nearly all but fine- to very coarse-sized grains are removed (Nedell and others, 1987). With no further sorting, therefore, eolian transport probably provides moderately sorted sand to the ice cover for deposition.

The sand may also be sorted by meltstreams flowing in the troughs between the ablation tables on the ice cover (Fig. 4). Sorting may occur as it does in terrestrial streams, with successively coarser or finer grains being provided to cracks and voids in the ice as the flow strength of the meltstream changes. Meltstreams may not be present at all early and late in the summer, however, limiting

the amount of time they might be an effective sorting mechanism.

Sorting also may take place by currents removing finer grains as the sediment settles through the water column; however, currents evidently are very weak in the ice-covered lakes because the ice cover prevents wind-generated currents. Until measurements are made, however, currents should not be precluded as a sorting mechanism.

Sorting may also take place as sediment settles through a still water column, because different grain sizes have different settling velocities (Blatt and others, 1972), and by avalanching and redeposition of sediment on the flanks of mounds (Love, 1982). These mechanisms, because they not only sort sediment but also grade it, are discussed below.

There are numerous units in the cores that are well-sorted to very well-sorted but not graded, and may have been sorted by these processes. These include some of the sand units that are interbedded with mat layers in the middle and upper portions of Cores F, G, and H. Specifically, they are Units 2, 4, 8, 10, 12, and a layer within Unit 9, of Core F; Units 3, 6, and some sand layers within Unit 7 of Core G; and, Units 3, 6, 8, and some sand layers within Unit 7 of Core H. In addition, well-sorted sand comprises most of Units 1, 3, 6, and 8 of Core C and most of the units of Core D. With the exception of

Unit 4 of Core A, there are no well-sorted units in Cores A and B, which are the shallowest cores. This suggests that water depth may be one of the factors affecting sorting, and that settling of grains through the water column may be a significant sorting mechanism.

Grading

Because of the unique mode of deposition through the ice cover, grading in Lake Hoare sediment probably does not occur by typical grading mechanisms such as sediment-gravity flows. Instead, grading may result from processes in effect in meltstreams on top of the ice, within the ice itself, after release of the sand from the ice, or on the flanks of mounds after initial deposition.

The changes in flow strengths of meltstreams may grade sand if the cracks or voids in the ice through which the sand is deposited remain open as the meltstreams flow over them or through them. As the flow strength of a meltstream weakens, progressively finer sand may be transported and the deposit may become normally graded. As the flow strength increases, progressively coarser grain sizes may be transported and the deposit may become inversely graded. If the sand is provided to multiple sources in the ice, normally and inversely graded units that are uniform in thickness may be deposited because the sand would be widely distributed. Units in the cores that are uniform in

thickness and graded include Units 1, 2, 4, 6 and 7 of Core C, Unit 6 of Core F, Unit 3 of Core G, and Unit 6 of Core H. These normally graded units differ from the normally graded, mounded units in that the latter fine both upward and outward, whereas these fine only upward.

Meltstreams, if they do grade sand, could produce both normally and inversely graded layers. All of the units listed above are normally graded except Unit 2 of Core C, which is inversely to normally graded. It may be significant that only one obviously inversely graded unit was observed in the cores; meltstreams may not be as important a grading mechanism as they are a sorting mechanism.

Normal grading may occur if the release of sand from the ice is rapid relative to the settling times in water of the different sizes of sand grains. Blatt and others (1972) have published empirical curves for the settling velocities of quartz spheres in water. Based on these curves, the settling velocities of the sand in Lake Hoare at a temperature of 0°C would range from a low of approximately 0.2 cm/sec for very fine sand to a high of approximately 25 cm/sec for very coarse sand. For sand to fall a depth of 10 m, as in divehole DH-1, it would take the very coarse grains as little as 40 seconds and the very fine grains as long as 1½ hours to settle to the bottom. For sand to fall a depth of 25 m as in divehole

RH-2, it would take the very coarse grains as little as 90 seconds and the fine grains as long as $3\frac{1}{2}$ hours to settle to the bottom. If a moderately sorted group of grains were released from the ice within a period of approximately $3\frac{1}{2}$ hours, or effectively "instantaneously", then sorting and normal grading would occur as the grains fell through the water due to differences in their settling velocities.

Unit 4 of Core A, for example, is normally graded. The center of the mound was to the left of the core, and this is reflected in the fact that the unit is coarser at the base and to the left, because the sand probably was released from a source in the ice above the center of the mound. If all of the sand in the unit had been released from the ice rather rapidly, or effectively instantaneously, the coarser grains would have reached the lake bottom first, causing the unit to be normally graded. It is also possible that this unit provides evidence of scattering of the finer grains by weak currents during deposition, because the coarser grains are near the center of the mound.

Unit 4 of Core A also is weakly stratified. The stratification, as shown by the orientation of the detrital mat pieces, probably was initially oriented subparallel to the top of the underlying unit, which slopes toward the left. By the time the finer grains reached the lake bottom, the stratification would have begun to be oriented

sloping away from the center of the mound. Other normally-graded, wedge-shaped or mounded units in the cores that may have been deposited by "instantaneous" release of sand from the ice are Units 1 and 2 of Core F, and Units 3 and 4 of Core G, from divehole RH-2.

The ice cover may be a significant source of inverse grading of the sand. The ice may initially, perhaps early in the summer, allow only finer grains through. This process was observed in a crack in the ice adjacent to a divehole (Nedell and others, 1987a). The crack narrowed with depth and had apparently prevented the larger grains from passing through the ice. The coarser grains may only get through the ice late in the season when the ice becomes sufficiently porous, resulting in inversely graded units. Water in the conduits may then gradually freeze during the fall and/or winter, producing normally graded layers.

Inverse grading due to avalanching also should be present in the cores on the sandflow toes of mounded units, similarly to avalanching on subaerial and subaqueous dune slipfaces (Lowe, 1982). Squyres and others (1991) stated that avalanching occurs on the flanks of some of the mounds near divehole GH-1 when the mounds are disturbed. None of the mounded units observed in this study, however, showed evidence of inverse grading due to avalanching.

In contrast to the normally-graded mounds, the wedge- or mound-shaped Unit 5 of Core C; Unit 4 of Core F; and

Units 2, 3, and 4 of Core H are not graded. These mounds may have been formed by a gradual, grain-by-grain release of sand from localized sources in the ice.

DISCUSSION

In general, the sedimentary structures described in this study reflect what are apparently lakewide sedimentary processes. In addition, multiple processes probably are occurring at any given time in a given area. In interpreting the specific sedimentary processes that are occurring, several hypotheses proposed by previous workers were tested. These hypotheses include questions about how sand is released from the ice and, more specifically, a test of a model of mound growth (Squyres and others, 1991); the effects that climatic changes (Wharton and others, 1992) and ice-sediment interactions (Andersen and others, 1993) may have on ice thickness changes, and the sensitivity of the sediment deposited in ice-covered lakes as an indicator of these changes (Wharton and others, 1989); and whether the ice-sediment system is in a steady state or is cyclic (Wharton and others, 1989).

Sedimentary Structures

It appears that sand mounds, although they may be the primary sedimentary structures on the lake bottom (Squyres and others, 1991), may not be as readily identifiable in the lake-bottom deposits as would be expected. Instead, non-mounded sand units seem to predominate, and many of these are not graded. The paucity

of graded units suggests that grains may get delivered to conduits in the ice rather slowly, that scattering of grains during settling from the ice cover is a common depositional mechanism, and/or that mounded units get reworked by weak currents. Perhaps much sedimentation takes place late in the summer, when the ice may become porous throughout its entire thickness over large areas (Squyres and others, 1991).

The model of Squyres and others (1991) for mound formation appears to be reasonable. Mounds do appear to differ in size and shape due to differences in sedimentation rates and water depths.

It is unclear, however, why no evidence of inverse grading due to avalanching on the flanks of the mounds was observed in the deposits analyzed in this study, because avalanching on the flanks of mounds has been observed. This is especially unusual for the mounded units of Core D, which was recovered from the flank of a mound. The units of Core D do, however, provide evidence that composite mounds probably exist, because they appear to slope toward the crest of the current mound from which the core was recovered.

If, as suggested above, a majority of the sediment is deposited late in the summer, then meltstreams may be a significant sorting and grading mechanism, although most of the other sorting and grading mechanisms discussed in

this paper - sorting by the ice cover, differential settlement of grains, and perhaps even sorting caused by weak currents - may also be in effect. The relative effectiveness of each of these mechanisms, however, has yet to be determined.

Sedimentary Sequences

Despite the fact that sedimentary structures vary between cores - even between cores from the same divehole location - some similarities in sedimentary sequences may occur in sediment deposited within the same setting. Cores A and B, for example, resemble each other in overall sequence in that they consist of lower portions that are sandier and upper portions that contain relatively thick accumulations of discontinuous, sandy mats that appear to be correlative between the two cores.

Sedimentary structures in Cores C and D differ because they were intentionally selected to contain potentially different sedimentary structures. Both cores do, however, consist of distinct layers of coarse and fine sand and reflect what appears to be an overall fining-upward sequence.

Cores F, G, and H display overall sedimentary sequences that are similar, except that Core F appears to contain only the upper two-thirds of what Cores G and H contain. They consist of sandy units in the lower part; interbedded

sand and mat units in the middle; and interbedded sand and sandy mat layers, with decreasing sand/mat ratios, at the top. Core G, however, differs from Core H in that Core G has smaller, better-defined mounded units in the middle portion. These mounds are similar to the well-defined mounded Units 1, 2 and 4 in the bottom portion of Core F.

Correlation of Cores

The discrete boundaries between mat layers in the upper portions of Cores F, G, and H should aid in the direct correlation of the layers. The only layer that may be correlative, however, is Unit 12 of Core F, a layer of well sorted, medium to coarse grained sand 5-7 mm thick near the top of the core, and Unit 8 of Core H, a layer of sand that is well-sorted, medium-grained, and 3-4 mm thick near the top of the core. Unit 12, however, is underlain by approximately 5 mm of thinly interbedded sand and sandy mat layers that are underlain by a sand layer 6-7 mm thick. This thicker sand layer is not present in the upper portion of Core H. Furthermore, neither of these thicker layers is present in Core G. It is questionable if any layers in Cores F and H are correlative.

Despite the overall similarities in sedimentary sequences, there are no sand layers that are obviously correlative between any of the cores. It is particularly

significant that there are no obviously correlative layers between cores recovered from near the same divehole because this indicates the extent to which sedimentation is heterogeneous in the lake. The ice does not appear to become thin enough or porous enough over even an area as limited in size as a divehole sampling area to deposit units that are homogeneous enough to recognize and correlate. Sedimentation does not appear to take place on a scale much larger than the size of a mound. In this study, the mounds that were measured during sampling ranged in size from 15 cm to 80 cm high. At the angle of repose, the largest of these mounds would be up to 3 m in diameter. The closest spacing between two sample locations was a few meters, and even this was not close enough to produce correlative sand layers. Even sand layers between cores spaced only 1.5 m apart were difficult to correlate (Squyres and others, 1991).

Even the non-mounded sand units were not correlative between the cores. The non-mounded structure of these units suggests that they were not deposited by a single source in the ice; however, the fact they they are non-correlative on such a small scale suggests that perhaps they were in fact deposited from localized sources but are not mounded because the sand was scattered by weak currents during or after deposition.

Perhaps as significant is the fact that no correlative sequences of layers, nor any single correlative sand layer, that may have been deposited during a lakewide sedimentary event were found in all of the cores. Squyres and others (1991) described how direct evidence was observed in 1987 that the Lake Hoare ice cover locally becomes porous throughout its entire thickness during the late summer. Theoretically, if the ice cover became porous enough everywhere to lose its entire sediment load, or if the ice cover melted completely, a lakewide sedimentary event would occur, and a layer that is correlative lakewide would be deposited. Based on the observed sediment density in the ice cover, the thickness of a layer produced by this loss of sediment load would range from approximately 7 to 23 mm (David Andersen, personal communication, 1993). If this layer resulted from complete melting of the ice, the scattered boulders present on the ice surface would be deposited as well. It is possible, however, that a lakewide sedimentary layer may not be deposited during such an event. Because sand is released from the ice in an inhomogeneous manner, it is possible that no lakewide correlative layer would be recognizable, even if all of the sand were eventually released.

Effects of Ice Thickness on Lake Hoare Deposits

Effects of Ice Thickness on Localization and Rates of Sedimentation

The thinning of the Lake Hoare ice cover observed from 1978-1989 (Wharton and others, 1992) is not reflected as a lakewide increase in sedimentation rates in the cores used in this study. A lakewide thinning of the ice during that period should be represented by a thin sand layer at the top of each core, but that was not observed. In fact, there appear to be no sand layers that are correlative between any of the cores.

The lack of sedimentary evidence of recent thinning of the ice cover may indicate that sedimentation rates have not yet increased enough to be reflected in the cores. Cores F, G, and H, for instance, all display a gradual transition from a period of more rapid sand accumulation, as displayed in the lower, sand-rich portions of Cores G and H, through a period of slowing sand accumulation as displayed in the interbedded sand and mats at the base of Core F and in the middle of Cores G and H, to a period of even slower sand accumulation in the mat-rich upper portions of all three cores. It is possible that the mat-rich sediment in the upper portions of these cores reflects a recent thick-ice episode, and that the wedge of sand at the top of Core A may be an indication that more rapid sedimentation has begun.

Core C contains a relatively thick, very fine- to fine-grained unit at the top, and Core D fines upward. Thickening of the ice may not only cause a slowing of sedimentation, it may also cause the ice to become less porous, and allow for the deposition of only finer grains.

The thickness of the ice cover on Lake Hoare may also be a factor controlling localization of sedimentation in the lake. Andersen and others (1993), in studying the ice covers of dry valley lakes, observed that lakes with ice covers thinner than about 4.5 m do not accumulate surface sediment or develop the rough topography observed on Lake Hoare and other lakes with thick ice covers. The lakes with thin ice covers are also apparently fairly permeable to water, gases and sediment during part of the year. The lakes with thinner ice covers, then, would be expected to have somewhat correlative deposits. More localized sedimentation probably occurs in those that have thicker ice covers because sediment trapped in meltwater pools on the rough surfaces of these lakes may be transported with the meltwater locally down through cracks or pores in the ice. The degree of localization of sediment observed in this study appears to support this idea.

Cyclicity of Sedimentation

Several authors (Simmons and others, 1986; Wharton and others, 1989; and Andersen and others, 1993) have

suggested that sedimentation in Lake Hoare may be cyclical due to alternate thickening and thinning of the ice cover. Simmons and others (1986) suggested that this cyclicity may be related to sediment loading in the ice. According to this idea, accumulation of sediment on the ice and absorption of solar radiation by aggregates of particles would cause surficial melting of the ice cover and rough ice topography. The rough ice would trap more sediment, causing even more melting, and thinning the ice. Loss of sediment from the ice due to thinning would cause the ice cover to thicken again, completing the cycle. Alternatively, this cyclicity may be related to cyclic climatic changes (Wharton and others, 1989; Andersen and others, 1993).

If the thinning of the ice cover on Lake Hoare were part of a cycle caused by sediment loading, the sedimentary sequence over the course of one cycle would be expected to be as follows: when the ice was thickest, deposition of sand would not be occurring and mats would be abundant; as increased sediment loading thinned the ice, thicker and more abundant sand units would be deposited until most or all of the sediment load had been released from the ice; with no sediment load, the ice would become thick again, possibly relatively rapidly, with little sand deposition. Mat layers would then grow on top of the thick sand layers, providing a sharp boundary between times of

most rapid sand accumulation and times of most abundant mat growth.

In contrast, if the thinning of the ice cover were part of a cycle of climatic change, a gradual change from the deposition of sand-rich to mat-rich sediment would occur, and the sedimentary sequence deposited over the course of one cycle would be expected to be as follows: during times of the thickest ice, sand would not be accumulating and mats would be abundant; as the temperature warmed and the ice thinned, thicker and more abundant sand units would be deposited; as the temperature began to cool and the ice became thicker again, the sequence would reverse and the sand units would become fewer and thinner and mat units more abundant until clastic sedimentation again ceased.

The sedimentary sequences observed in the cores used in this study do not display entirely either of these cyclic sequences. The overall sequence displayed in the cores does resemble the sequence that would be deposited during a gradual thickening of the ice: the sand units thin upward, and mat units gradually become more abundant. This sequence is particularly well displayed in Cores F, G, and H. This sequence, along with the overall upward-fining of Cores C and D, which may also have been caused by a gradual thickening of the ice, supports the idea that the sediment cores reflect a recent thick-ice episode at Lake Hoare.

A recent thick-ice episode at Lake Hoare may be represented nearly in its entirety in the cores from diveholes DH-1 and RH-2. The approximate age of the episode may be estimated by using the mat layers to constrain the age of at least the upper, mat-rich portions of the cores. The mat layers in the upper portions of Cores F, G, and H are used here because they are relatively stratiform and continuous. There are probably not more than 75 to 100 mat layers in the upper portions of these cores, and not more than 30 to 50 sand layers interbedded with them. If each sand or mat layer represents one year, then the upper portions of these cores may represent only 100 to 150 years. The entire thick-ice episode, then, may have lasted 100 to 150 years.

Although the thick-ice episode appears to be readily apparent in all of the cores, it is inexplicable why the sedimentary sequences in the cores do not reflect the observed recent thinning of the ice. If cycles due to climatic changes and cycles due to sediment loading do occur, however, they may be superimposed on each other, obscuring any clear evidence of either. Other possible reasons why the observed recent thinning of the ice is not reflected in the cores may be that either sediment is not as sensitive an indicator of ice thickness changes as previously believed, or that there is a time lag between when ice thickness changes occur and when they are reflected

in the lake-bottom sediment. If the latter is the case, then the time to sample the sediment again to look for ice thickness changes would be now, in anticipation that sedimentation may have caught up with the recent change in ice thickness.

CONCLUSIONS

An attempt was made in this study to interpret how the sedimentary processes in Lake Hoare are reflected in the sedimentary structures and stratigraphy of the lake-bottom sediments. The sedimentary processes themselves appear to be strongly controlled by the lake ice cover. Variations in sedimentation rates, for example, may be caused in part by the amount of available sediment, and in part by changes in the thickness of the ice cover. Variations in sedimentary structures from place to place appear to result from these variations in sedimentation rates. Mounded sand units, for instance, are in general thinner and more rounded in areas of slower sedimentation, such as at the nearshore and offshore Diveholes DH-1 and RH-2, respectively. The mounded sand units are larger and more conical in areas of more rapid sedimentation, such as at Divehole GH-1, where more sediment is available because it piles up against Canada Glacier.

Changes in sedimentation rates resulting from ice thickness changes are reflected in the cores as changes in sedimentary sequences. Most of the cores analyzed in this study display a decreasing sand/mat ratio from the bottom to the top of the core, with the upper portions of most of the cores being mat-rich. This sequence

suggests that a long-term slowing of sedimentation occurred, possibly resulting from a long-term thickening of the ice cover. No evidence was observed, however, of any lakewide increase in sedimentation rates resulting from the recently observed thinning of the ice cover.

One of the specific goals of this study was to analyze the structure of the unique sand mounds observed on the lake bottom; however, although sand mounds are a feature commonly observed on the lake bottom, mounded units are not as common as non-mounded units in these cores. We know the mounds exist, but perhaps they can't be sampled at such a small scale as a box core. Perhaps much of the "non-mounded" sand observed in the cores is actually broad mounds formed when sand is scattered, possibly by weak currents that were previously believed not to exist in Lake Hoare.

It was also expected that inverse grading due to avalanching of sand on the flanks of mounds would be observed in the cores, and it is inexplicable why it was not observed. Measurement of possible weak currents should be made because currents, if present, may also be scattering the sand on the flanks of mounds.

A problem that this author had in interpreting how sedimentary processes affect sedimentary structures is that the lake ice cover is not yet well enough understood. Sand has not yet been observed throughout the entire

thickness of the ice, and it is not yet known if or how the ice may sort the sand, or if meltstreams in the ice do indeed sort the sand. It is also not yet known how sand is released from the ice. Evidence from this study appears to indicate that both grain-by-grain release from the ice and "instantaneous" deposition probably occur. Rapid release of sand from the ice may cause the sand to become normally graded as it is deposited, whereas slower, grain-by-grain deposition probably results in sand that is not graded. Sorting and grading of the sand may also be caused by meltstreams flowing in troughs in the ice, or by processes active during the transport of sand through the ice.

This study has presented some evidence that the processes described above do occur. Multiple processes seem to be in effect, however, and the products of these processes appear to be superimposed upon one another.

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APPENDIX

Shapes of Units:

Uniform in Thickness

Wedge-Shaped

Lens- or Mound-Shaped

Relative Abundance*:

Rare

<2% of a unit

Sparse

2-10% of a unit

* Grains with >10% abundance included in grain size description

Sand Layering Description:

Stratified

With internal layering

Mat Description:

Stratiform

Layered

Detrital

Re-worked pieces

Mat Layering Description:

Stratiform, continuous

With layering intact

Stratiform, discontinuous

Layering not intact

Very Thin Layer

Having the appearance of being one layer

Sand Grain Sizes:

VF

Very fine-grained

F

Fine-grained

M

Medium-grained

C

Coarse-grained

VC

Very coarse-grained

UNIT NO.	THICKNESS (mm)	DESCRIPTION
4	30-85	Sand with sparse detrital mat pieces, wedge-shaped, sub-stratified; sand well sorted F-M at base and on left side, grading to well sorted VF-F at top and on right side; few very thin mat pieces 2-3 mm long oriented sub-parallel to stratification; sand/mat ratio approximately 50:1.
3	35-55	Interbedded organic-rich sand and sandy mat layers, sloping toward left; sand moderately sorted F-C(?) except for well sorted, F-M sandy cluster at left center; mat layers stratiform and continuous in top 2-3 mm only, otherwise stratiform, discontinuous and wavy, defining a weak stratification; sand/mat ratio approximately 10:1.
2	10-35	Sand, sloping toward left; moderately sorted F-C with rare VC; cluster of moderately sorted, M-VC at lower right.
1	0-20	Interbedded sand and mats, sloping toward left, truncated at bottom of core; sand moderately sorted F-C, organic-rich in clump near top; mats predominantly discontinuous, curled pieces up to 15 mm long except at top where sub-stratiform, discontinuous, with some carbonate crystals; sand/mat ratio approximately 2:1.

UNIT NO.	THICKNESS (mm)	DESCRIPTION
2	15-20	Sandy mat material; mat pieces randomly oriented, discontinuous and wavy; sand M-VC(?); sand/mat ratio approximately 1:4.
1	85-100	Sand, indistinctly stratified, moderately sorted F-VC with few finer- and coarser-grained clumps; organic-rich in upper 15-20 mm and in clumps below.

UNIT NO.	THICKNESS (mm)	DESCRIPTION
8	35	Sand, uniform in thickness and curved, convex upward, very well sorted VF-F, with few interbedded very thin mat layers at top.
7	10	Sand, uniform in thickness and curved, convex upward, well sorted, F-M on left to M-C on right.
6	15	Sand, uniform in thickness and curved, convex upward, well sorted M-C on left to very well sorted M on right.
5	0-12	Sand, pinch-out edge of a lens- or mound-shaped unit with upper boundary curved, convex upward, moderately sorted F-C.
4	10	Sand, uniform in thickness, moderately sorted F-C on left to well sorted F-M on right.
3	15	Sand, uniform in thickness, well sorted F with rare M-C; with interbedded pinch-out edge of lens- or mound-shaped unit of well-sorted, M-C sand.
2	35	Sand, uniform in thickness, inversely to normally graded; at base poorly sorted F-C with few VC, in middle well sorted M-VC, at top poorly sorted F-C with few VC.
1	25	Sand, uniform in thickness; well sorted, normally graded, F at base grading upward to VF-F at top 3 mm; with 3 interbedded pinch-out edges of lens- or mound-shaped units of sand, M-C and moderately sorted to F-VC and poorly sorted.

UNIT NO.	THICKNESS (mm)	DESCRIPTION
15	8-18	Sand, wedge-shaped, sloping toward the left; well sorted F with some C.
14	3	Sand, uniform in thickness, sloping toward the left; very well sorted VF.
13	10	Sand, uniform in thickness, sloping toward the left; moderately sorted F-VC.
12	35	Sand, normally graded, moderately sorted F-C with few VC at the base and at the middle of the right side to well sorted VF-F with rare C-VC at the top and on the left side.
11	10	Sand, uniform in thickness, sloping toward the left; well sorted F-M with few C-VC.
10	13	Sand, uniform in thickness, sloping toward the left; moderately sorted M-VC with rare VF-F flat-pebble gravel.
9	4	Sand, uniform in thickness, sloping toward the left; well sorted F-M with few C-VC.
8	15	Sand, uniform in thickness, sloping toward the left; well sorted C-VC.
7	3	Sand, uniform in thickness, sloping toward the left; well sorted F-M with few C-VC.
6	3-10	Sand, mounded, sloping toward the left; well sorted C-VC; pinches out toward left side of core.
5	3	Sand, uniform in thickness, sloping toward the left; well sorted F-M with few C-VC.
4	0-5	Sand, mounded, sloping toward the left; well sorted C-VC; pinches out toward left side of core.
3	4	Sand, uniform in thickness, sloping toward the left; well sorted F-M with few C-VC.
2	1-8	Sand, mounded, sloping toward the left; well sorted C-VC; pinches out toward left side of core.
1	4	Sand, uniform in thickness, sloping slightly toward the left; well sorted F-M with few C-VC.

UNIT NO.	THICKNESS (mm)	DESCRIPTION
13	3	Sandy mat layers; stratiform and curved, convex upward; sand moderately sorted F-C(?).
12	3-4	Sand; uniform in thickness and curved, convex upward; well sorted M-C; slightly organic-rich.
11	3-4	Sandy mat layers; stratiform and curved, convex upward; sand moderately sorted F-C(?); sand/mat ratio approximately 1:4.
10	5	Sand; uniform in thickness and curved, convex upward; well sorted M-C; slightly organic-rich.
9	30	Interbedded organic-rich sand and sandy mat layers; approximately 80% of sand layers moderately sorted F-C, approximately 20% moderately sorted M-VC; sand layers uniform in thickness and curved, convex upward, mat layers stratiform and curved, convex upward; sand/mat ratio approximately 2:1.
8	1	Sand topped with very thin mat layer, uniform in thickness and curved, convex upward, sand well sorted F; sand/mat ratio approximately 5:1.
7	3	Sand topped with very thin mat layer; uniform in thickness and curved, convex upward; sand moderately sorted F-M with few C; sand/mat ratio approximately 10:1.
6	3	Sand topped with very thin mat layer; uniform in thickness and curved, convex upward; sand normally graded, well sorted M-C with rare VC at base to well sorted F-M at top.
5	15	Sand topped with very thin mat layer; uniform in thickness and curved, convex upward; moderately sorted F-C; slightly organic-rich.
4	2-5	Sand; mounded; well sorted F-M with rare C; yellowish-orange discoloration at top.
3	1-4	Sand topped with very thin mat layer, curved, uniform in thickness except where it thins over underlying mounded units; moderately sorted F-C; organic-rich where thinnest.
2	2-14	Sand topped with very thin mat layer; mounded; thins over underlying mounded unit; well sorted M-C at right where thickest, grading to well sorted F-M and organic-rich at left where thinnest.
1	3-15	Sand topped with very thin mat layer; mounded; moderately sorted F-C in center grading to well sorted F-M and organic-rich at sides.

UNIT NO.	THICKNESS (mm)	DESCRIPTION
7	45	Interbedded organic-rich sand and sandy mat layers; sand layers uniform in thickness; sand well sorted F-M to moderately sorted M-VC; sand in sandy mat layers moderately sorted F-C(?); sand/sandy mat ratio approximately 2:1.
6	2-3	Organic-rich sand, well-sorted F-M with rare C, uniform in thickness except where it thickens at the left over underlying wedge.
5	0-10	Organic-rich sand; wedge-shaped; moderately sorted F-C.
4	2-6	Organic-rich, small mounded sand unit; moderately sorted M-VC; topped with very thin mat layer; sand/mat ratio approximately 7:1.
3	4	Organic-rich sand; uniform in thickness; normally graded F-M; sharp contact with overlying coarser lens.
2	3-5	Interbedded organic-rich sand and mat layers, 5-6 sand layers and 4-5 mat layers; sand moderately sorted F-C(?); mat very thin, stratiform.
1	85-87	Interbedded organic-rich sand and mat layers; sandy and wedge-shaped at base with overlying interbedded sand and sub-stratiform mat layers sloping toward left; sand moderately sorted F-C with few VC; mat layers very thin, discontinuous; sand/mat ratio approximately 15:1 at base grading to approximately 4:1 at top.

UNIT NO.	THICKNESS (mm)	DESCRIPTION
9	2	Sandy mat layers; sand moderately sorted F-C(?); mat layers substratiform and continuous.
8	3	Sand, uniform in thickness, slightly organic-rich, well sorted M.
7	35	Thinly interbedded organic-rich sand and sandy mat layers; sand layers uniform in thickness, very well sorted M to well sorted M-C; sand in sandy mat layers moderately sorted F-C(?) with one subangular pebble; sandy mat layers substratiform and continuous; sand/sandy mat ratio approximately 1:5.
6	10	Sand, uniform in thickness, normally graded, M at bottom approximately 10 mm to F-M at top approximately 2 mm.
5	10	Interbedded sand and mat layers; approximately 5 sand layers and 5 mat layers; uniform in thickness, curved toward the right over underlying units; sand organic-rich, moderately sorted VF-M to F-C; very thin layer of calcium carbonate crystals at top of unit; sand/mat ratio approximately 10:1.
4	15	Sand, portion of a mounded unit on right side of core, pinches out toward left; sand moderately sorted F-C; topped with a very thin mat layer; sand/mat ratio approximately 20:1.
3	0-7	Sand, portion of a mounded unit on left side of core, pinches out toward right; sand well sorted F with rare M-C; topped with a very thin mat layer; sand/mat ratio approximately 20:1.
2	0-45	Sand, moderately sorted F-C, wedge-shaped, topped with very thin mat layer, discontinuous to stratiform; sand mat ratio approximately 25:1.
1	15-55	Organic-rich sand wedge topped with interbedded sand and mat layers; sand moderately sorted F-C with rare VC; mat layers very thin, substratiform to discontinuous and curled, sloping toward the left; sand/mat ratio approximately 20:1.