Diatom-Inferred TP in MCWD Lakes

(Work Order #116-04)

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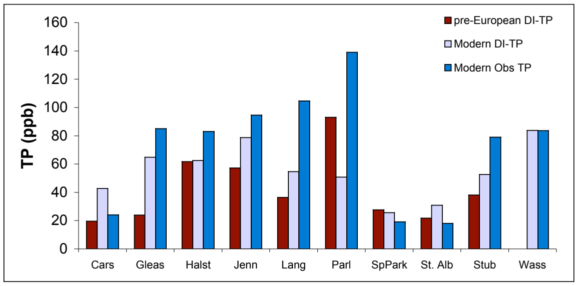
REPORT CONTENTS

PROJECT SUMMARY

Contemporary water quality data, surface sediment samples, and long sediment cores were collected from ten lakes and bays of the Lake Minnetonka watershed (Minnesota, U.S.A.) between April and September 2005 to compare background (pre-European settlement) or natural nutrient levels to modern nutrient conditions in these water bodies. Water quality data were collected from each site on five sampling dates between May and September 2005 and included Secchi depth, temperature, dissolved oxygen (DO), conductivity, pH, total phosphorus (TP), soluble reactive phophorus (SRP), total nitrogen (TN), chlorophyll a, dissolved organic carbon (DOC), color, sulfate, chloride, alkalinity, and silicate concentration. Monitoring indicated that the lakes and bays within the Lake Minnetonka watershed have modern water quality conditions ranging from mesotrophic bays on the main body of Lake Minnetonka to hypertrophic lakes and bays along the south, west, and northern reaches of the watershed

Long sediment cores (~1.9 m) were provisionally dated using digital imaging, magnetic susceptibility logging, and gamma analysis of 210-Pb and 137-Cs to determine levels of downcore sediments that corresponded to pre-European settlement (pre-1850 A.D.) sediments. A diatom calibration dataset based on diatom assemblages and modern water quality data from 89 Minnesota lakes, including the ten sites within the Lake Minnetonka watershed, was constructed to facilitate estimation of historical and modern total phosphorus levels from subfossil diatom assemblages. Two downcore samples, representing lake conditions before European settlement, and one upcore sample, representing modern lake conditons, were analyzed from each coring site for diatom microfossils. A transfer function generated from the calibraton dataset and based on each diatom species total phosphorus optimum was applied to all core diatom assemblages to reconstruct diatom-inferred total phosphorus (DI-TP) for pre-European and modern times.

Lakes and bays in the Minnetonka watershed generally showed three patterns of change between pre-European and modern nutrient conditon. Carsons, St. Albans, and Spring Park Bays have modern mesotrophic nutrient conditions and showed little change between pre-European and modern conditions. Gleason Lake, Stubbs Bay and Langdon Lake were all mesotrophic in pre-European times and are currently eutrophic to hypertrophic water bodies with modern TP levels above 60 ppb. Halsteds Bay and Jennings Bay were eutrophic systems in pre-European times and are currently eutrophic to hypertrophic (see summary figure). One lake, Parley, gave problematic reconstructions of DI-TP. Recommendation is to analyze the Parley Lake core in greater temporal detail, perhaps decadal resolution between 1800-2000 A.D. The sediment core recovered from Wasserman Lake was not long enough to recover pre-European sediments. Recommendation is to recover an additional 1-2 m of core using a Livingston corer.



INTRODUCTION

Federal and state regulations require that states identify impaired waters and develop plans to protect and remediate water quality. A critical component of developing sound management plans to improve impaired waters requires that we 1) know the modern sources of nutrients to a receiving water, and 2) have an understanding of the natural or background nutrient conditions of a lake or river. The former is normally determined through monitoring and experimental limnology, whereas the latter information is available from either modeling or paleoecology.

Paleoecology offers a unique tool to determine natural or background nutrient conditions in lakes. Lake sediments faithfully record changes that have occurred both within a lake and within its watershed. Broadscale application of sediment analysis to basic and applied research questions followed major advances in core dating in the 1970s and development of statistical tools for quantitative environmental reconstruction in the 1980s and 1990s.

Diatoms are microscopic, single-celled or colonial algae that are characterized by an ornamented two-part siliceous (glass) cell wall. They are often referred to as the "golden-brown" algae, a testament to their pigment complement. Diatoms are seasonally common to abundant in lakes, rivers, streams, and water bodies that experience even emphemeral moisture. Because of their siliceous cell walls, diatoms are usually well preserved in lake sediments and their presence, absence, abundance and community makeup provide a snapshot of historical environmental conditions and change. Diatom calibration and training sets have become powerful tools for paleoecological reconstruction and monitoring of surface water quality using standardized methods to reconstruct specific environmental parameters from modern or fossil diatom assemblages. Whereas earlier diatom-based methods provide qualitative measures of historical water chemistry or productivity using categorical indicator values (ter Braak and van Dam 1989, Agbeti 1992), the development of weighted averaging regression and calibration introduced a method of quantitative reconstruction of historical environmental variables (Birks *et al.* 1990a,b). The method develops a transfer function based on a training set of diatom assemblages from modern lakes and their relationship to select environmental gradients that independently explain variation in species distribution. The transfer function is next applied to historical diatom assemblages in sediment cores to mathematically reconstruct specific environmental variables. The weighted averaging method is statistically robust and based on ecologically sound organismal responses (ter Braak and Prentice 1988, Birks *et al.* 1990b). This approach has been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), dissolved organic carbon (DOC), and salinity (e.g. Anderson 1989, Fritz *et al.*, 1991, 1999, Dixit *et al.* 1992; Hall and Smol 1992).

For inferring historical total phosphorus (TP), diatom-based reconstructions have been adopted as the most powerful tool at hand (Fritz *et al.* 1993, Anderson and Rippey 1994, Reavie *et al.* 1995, Rippey and Anderson 1996). In the Minnesota region, the most readily applied training set was developed by Ramstack et al. (2003) from surface-sediment diatom assemblages from 55 Minnesota lakes of varying trophic status that were earlier cored for a regional mercury study (Engstrom *et al.* 1999). The application of Ramstack's training set has targeted "top-bottom" or modern vs pre-European reconstructions of environmental parameters (Heiskary and Swain

2002, Ramstack *et al.* 2004) and other Minnesota lake sediment records for post-European environmental change (Edlund and Engstrom 2001, Kingston *et al.* 2004). The 55 Minnesota Lakes training set has been further supplemented with additional lakes from southwest, westcentral and northern Minnesota to increase its utility and representation of other Minnesota lake types (Edlund and Kingston 2004, Edlund 2005)) and it has been used for the development of nutrient criteria in Minnesota lakes (Heiskary et al. 2004, Heiskary and Wilson 2005).

The location of the Lake Minnetonka watershed on an ecotone creates natural variability in lake type and water quality. Lakes in the western part of the watershed are similar to prairie lakes, lakes and bays in the northern and westcentral part of the basin are similar to lakes in the central hardwood forest region of Minnesota, and the main lake body bears resemblance to more northerly Minnesota lakes (Murchie 1985). Overlying this background and geologic variability are impacts on water quality resulting from 150 years of post-European settlement including water-level management, agriculture, diffuse and point source loadings, cottage and residential development, heavy recreational use, and exotic species (Megard 1970, 1972). As such, the modern Lake Minnetonka watershed has lakes and bays ranging in water quality from hypertrophic to nearly oligotrophic (Heiskary et al. 2006).

This study examines sediment cores from ten lakes and bays of the Lake Minnetonka watershed to reconstruct historical or pre-European total phosphorus concentrations and compares those to modern water quality conditions in the Lake Minnetonka watershed.

METHODS-CORING, DATING, AND SUBSAMPLING

Ten upgradient lakes and/or bays of Lake Minnetonka were identified by MCWD personnel for inclusion in this study (Table 1). The lakes range from Wasserman Lake in the southern watershed to Parley and Langdon Lakes in the western watershed, to the most northerly site, Gleason Lake. The bays of Lake Minnetonka that were studied included Carson and St. Albans Bay on the southern side, Halsted Bay on the western side, and Jennings, Stubbs, and Spring Park on the northern side of Lake Minnetonka.

A surface sediment sample (0-2 cm) was collected in September 2005 from the central depositional basin in each lake or bay with a Wiegner gravity corer. Samples were digested in 30% H_2O_2 for 2 hours at 85˚C, cooled, and oxidation byproducts removed with six rinses with distilled water. Subsamples of rinsed material were dried onto coverslips, which were subsequently attached to microslides with Naphrax mountant.

Piston cores were collected from the ten sites in the Minnetonka watershed in April 2005. Cores were taken using a drive-rod piston corer equipped with a 2.4 m long, 7.5 cm diameter polycarbonate barrel (Wright 1991). Target lakes and core recovery are provided in Table 1. Cores were vertically transported to shore, and the top 28-50 cm of unconsolidated sediment removed in 2-cm increments by vertical extrusion. The remaining core material was capped, sealed, and transported to 4°C storage.

Table 1. Lakes cored in April 2005 and length of core recovered. Water depth at the coring site is indicated in meters by Z(m).

Lake/Bay Name	Coring Location	County	Z (m)	Core length (cm)	Field and lab sectioned (cm)
Wasserman	44°50.461'N 93°40.377W	Carver	11.8	180	0-28
Parley	44°52.823'N 95°43.644W	Carver	5.96	190	0-36
Langdon	44°55.946'N 93°40.381'W	Hennepin	11.17	209	0-54
Gleason	44°58.719'N 93°29.577'W	Hennepin	4.80	187	0-44
Carsons B.	44°55.521'N 93°31.975W	Hennepin	7.93	207	0-49
St. Albans B.	44°54.466'N 93°33.089'W	Hennepin	11.19	198	0-43
Halsteds B.	44°54.895'N 93°41.361'W	Hennepin	9.07	195	0-40
Jennings B.	44°57.226'N 93°39.196'W	Hennepin	6.88	194	0-40
Stubbs B.	44°58.193'N 93°37.947'W	Hennepin	9.84	188	0-36
Spring Park	44°55.990'N 93°37.478'W	Hennepin	8.75	192	0-40

Cores were subdivided into 1.4-m long sections for magnetic susceptibility logging on a Bartington MS2 core logging sensor with an automated trackfeed. Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. Increases in magnetic susceptibility signatures may be correlated to erosion from land use changes including land clearance, increased terrestrial-derived sediments, and paleosols. Alternatively, decreases in magnetic susceptibility can result from increased autochthonous productivity, for example from lake eutrophication. Susceptibility measures were taken at 1-cm intervals, which integrated a signal over a 5-10-cm length of core. Data were spliced at core breaks for plotting. Following susceptibility logging, cores were split lengthwise, physically described, and digital images taken of each core section using a Geoscan digital core scanner. Following scanning, cores were returned to storage at 4°C.

Two to three downcore samples from each core were selected for measurement of unsupported ^{210}Pb using a high-resolution germanium well gamma detector and multichannel analyzer (Table 2). The presence of any unsupported ^{210}Pb in a core subsample would be an indication that the sample is dated at less than seven half-lives of ^{210}Pb, approximately 150 years, or from a time period of very high sedimentation that would mask an unsupported ^{210}Pb signal. From this analysis we determined whether downcore sediment levels were deposited before European settlement. As a further check of core dates, 137Cs was also quantified in the core samples. 137-Cs is a isotopic product of atmospheric nuclear bomb testing and its presence indicates sediments deposited after 1950.

Table 2. Unsupported 210-Pb quantified from select core depths from Minnetonka area lakes and bays. Sample depths and 210-Pb depths do not include sediment sectioned in the lab or field but match with depths given on Appendix Figs 1-10; parenthetical values are corrected for actual core depths.

Lake Name	Lake ID	County	Unsupported 210-Pb depths (cm)	Excess 210-Pb (as 214-Pb)	Cs-137 corrected (pCi/g)
Wasserman	18-0088	Carver	95 (123)	1.6492	1.529
			135* (163)	1.3579*	2.387*
Parley	18-0386	Carver	100 (136)	0.4493	0.000
			142 (178)	0.0746	0.000
Langdon	27-0125	Hennepin	115 (169)	0.000	0.000
			145 (199)	0.000	0.000
Gleason	33-0015	Hennepin	75 (119)	0.000	0.000
			137 (181)	0.000	0.000
Carsons B.	61-0006	Hennepin	55 (104)	0.000	0.000
			110 (159)	0.000	0.000
			145 (194)	0.000	0.000
St. Albans B.	71-0016	Hennepin	50 (93)	0.000	0.000
			95 (138)	0.000	0.000
			100 (143)	0.000	0.000
Halsteds B.	72-0013	Hennepin	125 (165)	0.000	0.000
			147** (187)	1.3231**	0.430**
Jennings B.	73-0273	Hennepin	80 (120)	1.3617	0.000
			120 (160)	0.000	0.000
			145 (185)	0.000	0.000
Stubbs B.	76-0033	Hennepin	105 (141)	0.3477	0.000
			145 (181)	0.000	0.000
Spring Park	-	Hennepin	75 (115)	0.2284	0.000
			110 (150)	0.000	0.000
			147 (187)	0.000	0.000

*The core from Wasserman Lake is too short to recover pre-European sediments.

**The lowermost level of the Halsteds Bay core shows contamination from upcore sediments as a result of core extrusion. The 125 cm (165 cm) section was used for diatom analysis.

The core surface sample, the uppermost core sample found with no unsupported ^{210}Pb, and a second sample taken from sediments deposited ca 50 years earlie were processed for diatom analysis as above (Table 3). Mean linear and bulk sedimentation rates calculated from the NGP and WCBP lakes in the Ramstack (2003) lake set were used to calculate a pre-1850 SW Minnesota linear sedimentation rate (2.17 +/- 0.32 mm/yr), which guided our downcore sampling. Without more detailed dating analysis on each core, we can only be certain that the two presettlement samples are dated from greater than 150 years before present and were deposited approximately 50 years apart; we cannot assign a specific calendar date to those samples based on gamma analysis and magnetic susceptibility logging.

Table 3. Core samples analyzed for diatom microfossils. Depths shown with two values represent, first, values corresponding to depths shown on Appendix Figs 1-10, and parenthetical values which are actual core depths.

Lake Name	Lake ID	County	Core samples analyzed for diatoms (cm)
Wasserman	18-0088	Carver	2
Parley	18-0386	Carver	2
			142 (178)
			147 (183)
Langdon	27-0125	Hennepin	2
			115 (169)
			120 (174)
Gleason	33-0015	Hennepin	2
			75 (119)
			80 (124)
Carsons B.	61-0006	Hennepin	2
			55 (104)
			60 (109)
St. Albans B.	71-0016	Hennepin	2
			50 (93)
			55 (98)
Halsteds B.	72-0013	Hennepin	2
			125 (165)
			130 (170)
Jennings B.	73-0273	Hennepin	2
			120 (160)
			125 (165)
Stubbs B.	76-0033	Hennepin	2
			145 (181)
			150 (186)
Spring Park	-	Hennepin	2
			147 (187)
			152 (192)

METHODS-ENVIRONMENTAL DATA

Contemporary water chemistry and physical measures were collected on five sampling dates between May and September 2005 from 10 lakes and bays in the Lake Minnetonka watershed using standard sampling and analytical methods. Parameters sampled included: secchi depth, temperature, dissolved oxygen, conductivity, pH, chlorophyll a, total phosphorus, soluble reactive phosphorus, total nitrogen, dissolved organic carbon, color, sulfate, chloride, alkalinity or acid neutralizing capacity, and dissolved silicate. Summaries of water quality data and physical measures of lake and watershed morphometry were provided by Dr. Lorin Hatch

(MCWD). For integration with the Minnesota diatom calibration set, annual (ice-free) means were calculated (Table 4).

METHODS-DIATOM ANALYSIS

Diatom remains were counted in surface sediment samples (0-2 cm) from short gravity cores collected in September 2005 from all ten lakes and bays in the Lake Minnetonka watershed. A total of 400 diatom valves was counted along up to six random transects on Naphrax-mounted microslides using either an Olympus BX5O or Leitz Ortholux light microscope fitted with full immersion optics capable of 875-1250X magnification and N.A.>1.30. Our analysis used the same enumeration criteria as Ramstack (2003), i.e. diatoms were counted when over 50% of the valve was present or when a distinct valve fragment was present (e.g., central area of *Amphora libyca* or valve end in *Asterionella formosa*). Raw counts were converted to percent abundance relative to all diatom microfossils counted.

Diatom remains were also counted from three samples from each of nine sediment cores using the same methods. The Wasserman Lake core was not long enough to recover pre-European sediements. The uppermost sample from 0-2 cm represents contemporary lake conditions. The two downcore samples from each core represent "pre-European" settlement conditions in the lakes.

Diatoms were identified using floras and monographs by Hustedt 1927-1966, 1930, Patrick and Reimer 1966, 1975, Collins and Kalinsky 1977, Camburn *et al.* 1978, 1984-1986, Krammer and Lange-Bertalot 1986, 1988, 1991a, b, Cumming *et al.* 1995, Reavie and Smol 1998, Camburn and Charles 2000, and Fallu et. al. 2000.

METHODS-NUMERICAL ANALYSIS

Water quality and morphometric data from the ten Lake Minnetonka watershed sites were appended to a 79 Minnesota lake data set (Ramstack et al. 2003, Edlund and Kingston 2004). Similarly, the diatom assemblages from the Minnetonka watershed sites were appended to the 79 lake data set using image files at SCWRS to harmonize taxonomy among the datasets. Relationships among environmental variables and species distributions for the full 89 Minnesota lakes in the new training set were explored using canonical correspondence analysis (CCA), a multivariate ordination technique for direct gradient analysis (ter Braak & Prentice, 1988) available in the CANOCO 4 software package (ter Braak and Smilauer 1998). Species present at greater than 1% relative abundance in two or more samples or at greater than 5% relative abundance in one sample were included in ordination analyses; the same selection criteria were used by Ramstack *et al.* (2003).

The following ten environmental variables (variously transformed to approximate normal distributions) were used in the analysis: log TP, log Zmax, pH, log Color, logx+1 Cl, Cond, ANC, SD, log TN, and logx+1 chla. Ecoregion was omitted from this analysis; log Larea, log

Wshed, and log Zmean were also omitted because of missing data in the MCWD sites (CANOCO will treat missing environmental data as zeros). A total of 157 diatom species was included in the ordination analyses. The distribution of species among samples was initially explored with detrended correspondence analysis (DCA) and correspondence analysis (CA), respectively, to determine gradient length and examine the variation in the species data. A canonical correspondence analysis (CCA) with forward selection was used to explore the relationship between the species data and the environmental variables, and to identify a subset of environmental variables that independently explained a significant portion of variance in the species data ($p<0.05$). For each environmental variable identified in forward selection a constrained CCA was run to test significance and percent variance explained. For all CCA ordinations, rare taxa were downweighted and Monte Carlo permutation run to test for significance. Environmental variables that independently explained significant variation in the species distributions can then be used as predictor variables to develop transfer functions using weighted averaging regression and calibration (Birks *et al.*, 1990).

A transfer function for reconstructing logTP was developed using weighted averaging (WA) regression with inverse deshrinking and bootstrap error estimation (C2 software; Juggins 2003). The strength of the transfer function was evaluated by calculating the squared correlation coefficient (r^2) and the root mean square error (RMSE) between the observed logTP with the model estimates of logTP for all samples. Bootstrapping is used in model validation to provide a more realistic error estimate (RMSEP, the root mean square error of prediction) because the same data are used to both generate and test the WA model (Fritz *et al.* 1999). Outliers were identified from plots of model and bootstrap residuals; samples with residuals greater than the standard deviation of logTP ($SD_{logTP}=0.46$) in the training set were removed for development of the final transfer function. Reconstructed estimates of TP (diatom-inferred TP, or DI-TP) for each surface and downcore sample were determined by taking the logTP optimum of each species, weighting it by its abundance in that sample, and determining the average of the combined weighted species optima. Downcore reconstructions of environmental variables are strongest if the fossil assemblage is analogous to a modern sample in the training set. The software ANALOG 1.6 (Birks, unpublished) was used to calculate a minimum dissimilarity coefficient (DC) between each fossil sample and its nearest modern analogue using the squared chi-squared distance metric. A minimum DC score of less than 0.4067 (the first percentile of distance distributions among the modern samples), 0.6699 (the fifth percentile), and 0.8598 (the tenth percentile) identified a fossil sample with a very good, good, or poor modern analogue, respectively.

RESULTS & DISCUSSION-ENVIRONMENTAL DATA

Annual (ice-free) means were calculated for all environmental data based on five samplings done from May-Sept 2005. The lakes and bays in the Minnetonka watershed vary widely in water quality, size, and depth. Lakes varied from 4.9 to 13. 4 m depth and and covered a three-fold range in lake area (Table 4c). Mean Secchi depths ranged from less than 1 m (Langdon Lake) to over 3.5 m in Lake Minnetonka's St. Albans Bay (Table 4a). Sites ranged from mesotrophic to hypertrophic with several bays of Lake Minnetonka (St. Albans and Spring Park) with less than

20 ppb TP and ca. 5 ppb chl *a* to lakes on the west and north side of the watershed with greater than 100 ppb TP and over 40 ppb chl *a* (e.g. Langdon and Parley Lakes).

Table 4a. Annual (ice-free) average of physio-chemical water quality data from ten lakes or bays in the Lake Minnetonka watershed (data from Dr. Lorin Hatch, MCWD)

Site	Site code	Secchi	Temp	DO	Cond	pH	Chla	TP	SRP	TN
		m	°C	ppm	µmho/cm		ppb	ppb	ppb	ppm
St. Albans Bay	LAL01	3.62	21.5	9.92	489	8.47	5.04	18	2.5	0.72
Carsons Bay	LCS01	3.16	20.8	10.2	514	8.42	5.23	24	2.5	0.76
Gleason Lake	LGL01	1.94	21.4	10.3	681	8.4	33.5	85	12	1.11
Halsteads Bay	LHL01	1.42	21.6	10.8	501	8.35	43.6	83	8.7	1.55
Jennings Bay	LJE01	1.12	21.6	10.9	544	8.4	57.9	94.6	3.98	1.5
Langdon Lake	LLA01	0.96	21.8	11.9	458	8.48	42.1	105	10.1	1.75
Parley Lake	LPR01	1.08	21.5	12.2	416	8.56	39.5	139	7.2	2.08
Spring Park Bay	LSP01	2.86	21.2	10.3	474	8.42	5.87	19.2	2.5	0.72
Stubbs Bay	LSU01	1.44	21.4	10.5	565	8.5	47.4	79	11.2	1.64
Wasserman Lake	LWS01	0.78	21.2	11.4	386	8.4	51	83.6	7.14	1.84

Table 4b. Annual (ice-free) average of physio-chemical water quality data from ten lakes or bays in the Lake Minnetonka watershed (data from Dr. Lorin Hatch, MCWD)

Site	Site code	DOC	Color	SO4	Cl	Alk.	Silic.	ANC
		ppm	APHA	ppm	ppm	ppm	ppm	ueq/l
St. Albans Bay	LAL01	12.9	11.4	4.26	48.3	121	0.25	2428
Carsons Bay	LCS01	11.6	8.9	4.68	43.9	140	0.76	2802
Gleason Lake	LGL01	12.9	30.7	2.82	107	95.4	2.15	1908
Halsteads Bay	LHL01	18.2	29.4	5.86	33.6	155	3.19	3104
Jennings Bay	LJE01	21.5	37.2	6.78	41.2	160	3.17	3192
Langdon Lake	LLA01	17	40	3.28	36.3	131	0.41	2612
Parley Lake	LPR01	19.6	46.2	4.88	28.2	130	3.98	2604
Spring Park Bay	LSP01	12.7	12	4.7	38.5	136	0.8	2726
Stubbs Bay	LSU01	19.7	33.2	5.82	52.8	149	1.97	2976
Wasserman Lake	LWS01	21.6	37.8	3.06	21.9	128	0.98	2554

Table 4c. Annual (ice-free) average of physio-chemical water quality data from ten lakes or bays in the Lake Minnetonka watershed (data from Dr. Lorin Hatch, MCWD)

Site	Site code	Zmax	Zmean	Lake Area	Wshd Area
		m	m	ha	ha
St. Albans Bay	LAL01	13.4	4.3	66.4	-
Carsons Bay	LCS01	8.8	-	-	-
Gleason Lake	LGL01	4.9	2.4	63.1	991.1
Halsteads Bay	LHL01	11.0	4.0	218.9	7476.4
Jennings Bay	LJE01	7.9	3.4	119.8	4370.4
Langdon Lake	LLA01	11.6	2.4	58.3	368.7
Parley Lake	LPR01	6.1	2.1	98.3	4965.3
Spring Park Bay	LSP01	11.0	-	165.1	-
Stubbs Bay	LSU01	11.3	4.9	76.1	711.1
Wasserman Lake	LWS01	12.5	3.0	61.9	1107.7

RESULTS & DISCUSSION-89 LAKES CALIBRATION SET AND TOTAL PHOSPHORUS TRANSFER FUNCTION

Results of the CCA indicated that the 10 environmental and physical variables collectively explain 30.2% of the variance in the species data with 10.6% and 6.4% of the variance explained by axes 1 and 2, respectively.

Because of correlation among environmental variables, a second CCA was run with forward selection and identified that the following six variables (in this order), log TP, log Zmax, pH, log Color, logx1 Cl, Cond, each independently explain significant variation in the species data, and together account for 26.0% of the variance in the diatom data or 86.1% of the variance explained by all environmental variables.

Using a constrained CCA, the significance of each variable was tested ($p<0.05$). Total phosphorus was the most explanatory variable, independently accounting for 8.8% of the variance in the species data. The other eight environmental and physical variables and the percent variance explained included: Zmax (5.1%), pH (3.8%), color (2.6%), chloride (2.6%), conductivity (3.1%).

A CCA biplot of the six environmental variables identified with forward selection shows the high correlation of logTP with axis 1 (Fig. 1, inset). The environmental variables most strongly correlated with axis 2 are color, pH, and chloride. When all 89 Minnesota lakes are plotted in ordination space they cluster by ecoregion (Fig. 1). Lakes from the WCP and NGP are positioned on the left of axis one at the upper end of the TP vectors. Lakes in the CHF are centrally positioned in the ordination. Metro lakes cluster to the right on axis 1 and negative on axis 2, an indication of their modern mesotrophy and elevated chloride levels. Lakes of the NLF are clustered in the upper right of the ordination; this group of lakes is characterized by low productivity, stained waters, and contain the lowest pH lakes in the data set. The ten lakes and bays in the Minnetonka watershed plot centrally on axis one and negative on axis two. The major bays of Lake Minnetonka, Carsons, Spring Park and St. Albans plot among the CHF and more productive NLF lakes, a testament to their higher water quality. The hypertrophic lakes, Wasserman, Gleason, and Jennings, plot toward the WCP and NGP lakes, and the remaining lakes plot among the Metro and deep WCP lakes.

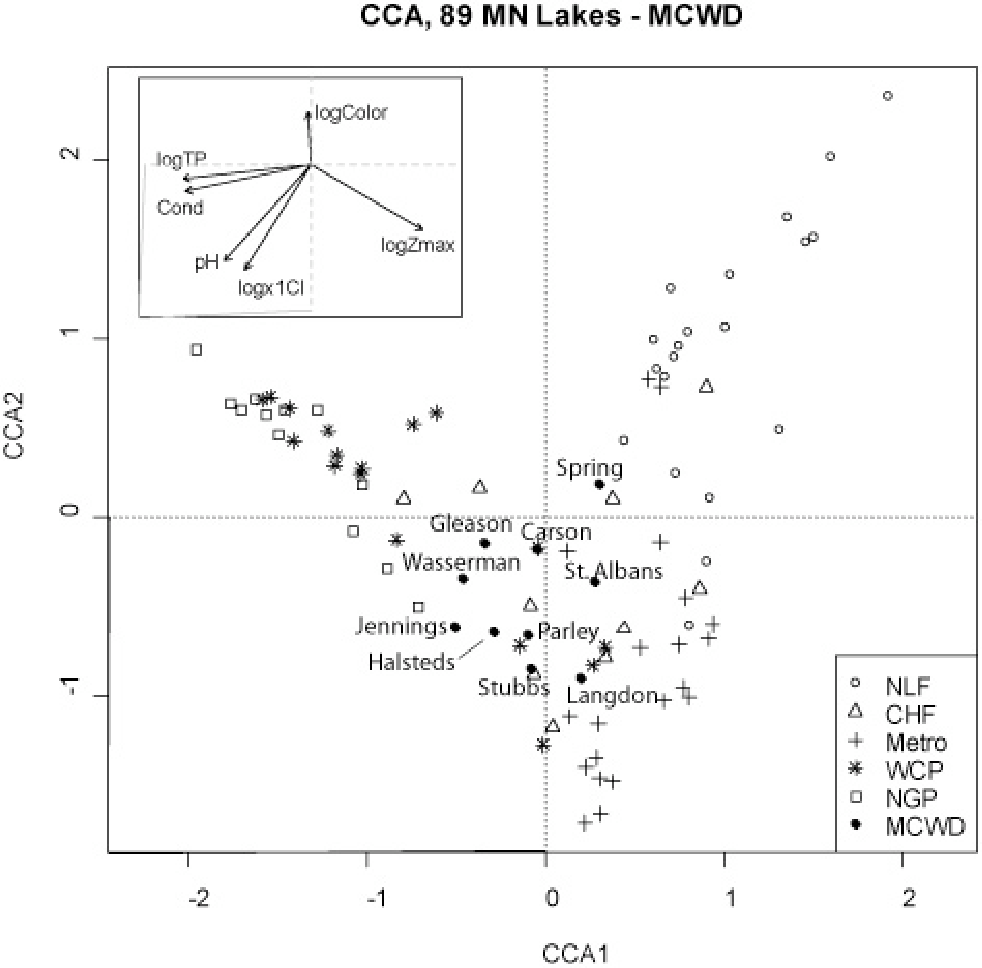


Figure 1. CCA biplot of 89 Minnesota lakes in species-environment multivariate space; location in multivariate space of ten lakes and bays in the Lake Minnetonka watershed labelled (MCWD). Inset graph shows the six major environmental gradients; gradients aligned with axis 1 and longer vectors are most explanatory. Other Minnesota lakes are plotted by symbols which correspond to ecoregions (Omerick 1987): NLF-northern lakes and forest, CHF-northcentral hardwoods forest, Metro-lakes within the Minneapolis-St. Paul metropolitan area, WCP-western corn belt plains, NGP-northern glaciated plains.

Because TP was identified as the most explanatory environmental variable using CCA, it was available as a predictor variable to develop a mathematical transfer function to estimate logTP from modern or fossil diatom assemblages. Weighted averaging using inverse deshrinking (WA_{inv}) and bootstrap error estimation was chosen to develop the transfer function. Initial model results and error estimates based on all 89 lakes identified three lakes as outliers, (Dickman, George -Blue Earth Co., and Loon -Jackson Co.), which were removed from the final WA_{inv} model. The performance (Fig. 2) of the final TP model (86 lakes) was evaluated using the squared correlation coefficient between observed and diatom-inferred total phosphorus ($r^2 = 0.832$) and the apparent root mean square error (RMSE = 0.181). Because the same samples are used to develop and test the model, bootstrapping is used for model validation and provides a more realistic error estimate, the root mean square error of prediction ($RMSEP_{boot} = 0.208$). Because averaging is used to in both the regression and calibration steps in transfer function development, weighted averaging models tend to overestimate low TP values and underestimate high TP values. Inverse deshrinking is thus used to correct initial reconstructed TP values. Initial inferred logTP values calculated with our transfer function were corrected with the following deshrinking equation:

$$\text{final logTP} = (\text{initial logTP})*(-0.860)+1.533$$

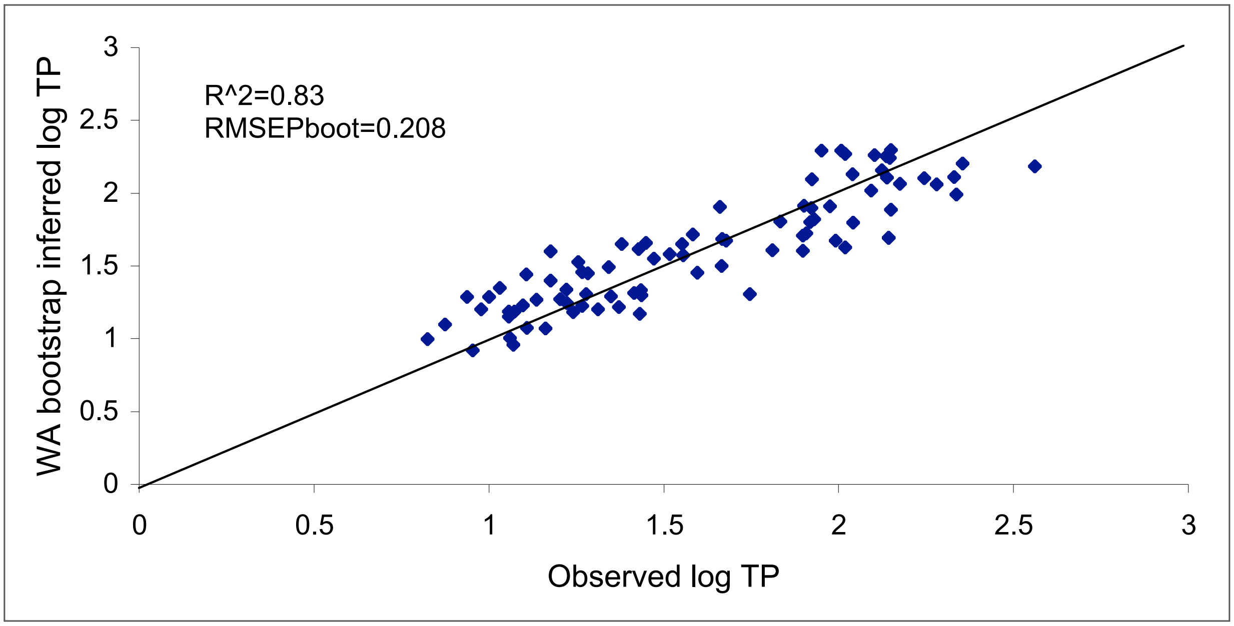


Figure 2. Performance criteria for the 89 Minnesota lake diatom transfer function used for MCWD diatom-inferred TP reconstructions.

RESULTS & DISCUSSION-SEDIMENT CORE RECONSTRUCTIONS

The logTP transfer function was applied to downcore diatom assemblages in nine sediment cores recovered in 2005 from sites in the Minnetonka watershed to calculate diatom-inferred total phosphorus (DI-TP). From each core, two samples representing sediments deposited before regional European settlement provide a measure of baseline or natural nutrient conditions in these lakes. Presettlement conditions can be compared to a DI-TP estimated from a third core sample (0-2 cm) representing modern conditions, the DI-TP based on training set development, and to monitoring records collected by MCWD in 2005 (Table 5). There is an overall trend in the lakes of increased DI-TP in modern vs pre-European conditions (Fig. 3). Several of the lakes/bays with good modern water quality show little change between pre-European and modern DI-TP. Summaries of DI-TP

Carsons Bay is currently mesotrophic with observed annual TP of approximately 24 ppb TP. A mean pre-European DI-TP of 19.5 ppb TP suggests that modern Carsons Bay nutrient dyamics are similar to historical conditions. Modern DI-TP reconstructed slightly higher than observed values.

Gleason Lake experiences wide variation in modern TP levels of 25-120 ppb with a annual mean of 85 ppb TP. Modern DI-TP of 65 ppb TP was similar to observed values. Based on pre-European DI-TP values of 24 ppb TP, we can conclude that Gleason Lake has been heavily impacted since European settlement and seen a shift from mesotrophic to very eutrophic conditions.

Halsteds Bay, on Minnetonka's western side, is currently a very productive portion of Lake Minnetonka with a mean observed TP of 83 ppb. Modern DI-TP was estimated at 62.5 ppb, well within the range of observed values. Historical DI-TP estimates of 62 ppb TP suggest that Halsteds Bay has long been a very productive water body with similar nutrient dynamics between historical and modern times.

Jennings Bay is located in the northwest portion of the Minnetonka watershed and is currently a eutrophic to hypertrophic bay with observed TP values of 48-137 ppb (annual mean 95 ppb TP). Modern DI-TP reconstruction was 79 ppb TP whereas pre-European DI-TP values were estimated at 57 ppb TP suggesting that although Jennings Bay has long been a productive system, modern conditions are more eutrophic.

Langdon Lake is located on the western side of the Minnetonka watershed and shows a similar trend to Jennings Lake. Modern observed TP ranges from eutrophic to hypertrophic (76-127 ppb TP) with an annual observed mean of 95 ppb TP. Modern DI-TP estimates were slightly lower than observed values with a mean modern DI-TP of 55 ppb. Pre-European DI-TP was estimated at 36 ppb TP which indicates that modern Langdon Lake is rather impacted by excess nutrients.

Parley Lake is the most problematic lake in this analysis. Modern Parley Lake is hypertrophic with an observed annual mean TP of 139 ppb (range 72-196 ppb). Modern DI-TP reconstructed much too low at 51 ppb TP and pre-European DI-TP was estimated very high at 93 ppb.

Surprisingly, all core samples had good analogues in the modern training set of 89 Minnesota lakes. As expected Parley2 had its best analogue in the modern Parley Lake sample. Parley142 and Parley147 were most similar to lakes in the highly agriculturally impacted Western Corn Belt Plains Goose Lake (Lyon Co., 42-0093) and Cottonwood Lake (Cottonwood Co., 17-0022), respectively. I would not be comfortable suggesting that Parley Lake was hypertrophic in pre-European times and would recommend that a more detailed analysis of the Parley Lake core be completed.

Spring Park is a bay along the north shore of the upper portion of Lake Minnetonka. It currently has very good mesotrophic water quality (mean observed 19 ppb TP) with little annual variation in total phosphorus (range 16-22 ppb). Modern DI-TP provided an estimate similar to observed values with 25.6 ppb TP. Pre-European DI-TP suggests that nutrient dynamics in Spring Park Bay are little changed in modern times. Reconstruction of pre-European DI-TP of 27.5 ppb TP was just slightly higher than modern observed or modern DI-TP.

St. Albans Bay is along Minnetonka's southeast shore and enjoys the best modern water quality of the ten sites sampled in 2005. Mean annual observed TP was a respectable 18 ppb TP (range 13-22 ppb). The modern DI-TP estimate was slightly higher at approximately 31 ppb. Historical estimates of pre-European DI-TP were similar to modern observed and inferred values at 21.7 ppb TP and suggest that modern conditions in St. Albans Bay are similar to historical nutrient conditions present before European settlement.

Stubbs Bay is well-separated from the main body of Lake Minnetonka and is currently eutrophic. Modern water quality observations recorded 2005 TP values of 58-101 ppb (mean 79 ppb TP). A modern mean DI-TP value of 52.6 ppb reconstructed a similar story of modern condition in Stubbs Bay. Pre-European estimates of TP suggest that Stubbs Bay was historically a mesotrophic system (pre-European DI-TP 38 ppb), which has in modern times become eutrophic to periodically hypertrophic.

Wasserman Lake is located in the agricultural belt on the very southern reaches of the Lake Minnetonka watershed. Modern Wasserman Lake is eutrophic with observed and DI-TP values of 84 ppb. The core taken from Wasserman Lake was not long enough to recover pre-European sediments, which is a likely consequence of very high post-settlement sedimentation rate. Recommendation is to take a second core using a Livingston corer to recover older sediments.

Lakes and bays in the Minnetonka watershed generally showed three patterns of change between pre-European and modern nutrient conditon. Carsons, St. Albans, and Spring Park Bays have modern mesotrophic nutrient conditions and showed little change between pre-European and modern conditions. Gleason Lake, Stubbs Bay and Langdon Lake were all mesotrophic in pre-European times and are currently eutrophic to hypertrophic water bodies with modern TP levels above 60 ppb. Halsteds Bay and Jennings Bay were eutrophic systems in pre-European times and are currently eutrophic to hypertrophic (Fig. 3).

Table 5a. Diatom-inferred total phosphorus (DI-TP) reconstructions from training set surface sediment samples (surf) and sediment core samples (number following lake name is core depth in cm). The uppermost core samples represent modern lake conditions (ca. 2002-2005 AD); the two deepest samples from each core represent sediments deposited before regional European settlement. The 2005 mean epilimnetic TP and range of observed TP values are listed for all ten sites. The dissimilarity coefficient (DC) is calculated as the squared chi-squared distance between a fossil sample and its nearest modern analog among the 76 lakes in the logTP transfer function. A minimum dissimilarity coefficient (DC) score of less than 0.4067 (the first percentile of distance distributions among the modern samples), 0.6699 (the fifth percentile), and 0.8598 (the tenth percentile) identified a fossil sample with a very good, good, or poor modern analogue, respectively.

Site	Site/core depth	2005 observed mean TP	2005 observed TP range	DI-TP	DC	Modern analogue
	cm	ppb	ppb	ppb	-	-
Carson Bay	Carson (surf)	24	19.5-27.5	44.5	-	-
	Carson2	-	19.5-27.5	40.9	0.4717	VG
	Carson55	-	-	20.0	0.6283	G
	Carson60	-	-	19.0	0.6482	G
Gleason	Gleason (surf)	85	25-120	69.7	-	-
	Gleaso2	-	25-120	59.8	0.3537	VG
	Gleaso75	-	-	26.2	0.8142	P
	Gleaso80	-	-	21.6	0.6356	G
Halsted	Halsted (surf)	83	59.8-104	66.7	-	-
	Halste2	-	59.8-104	58.2	0.5428	G
	Halst125	-	-	80.6	0.6881	P
	Halst130	-	-	43.0	0.8523	P
Jennings	Jennings (surf)	95	48-137	85.8	-	-
	Jennin2	-	48-137	71.5	0.4796	G
	Jenni120	-	-	65.6	0.9832	P
	Jenni125	-	-	48.9	0.8793	P
Langdon	Langdon (surf)	105	76-124	49.4	-	-
	Langdo2	-	76-124	60.0	0.5411	G
	Langd115	-	-	30.2	0.5595	G
	Langd120	-	-	42.8	0.7075	P
Parley	Parley (surf)	139	72-196	54.0	-	-
	Parley2	-	72-196	47.5	0.4641	G
	Parle142	-	-	85.4	0.4698	G
	Parle147	-	-	100.6	0.4891	G

Table 5b. Diatom-inferred total phosphorus (DI-TP) reconstructions from training set surface sediment samples (surf) and sediment core samples (number following lake name is core depth in cm). The uppermost core samples represent modern lake conditions (ca. 2002-2005 AD); the two deepest samples from each core represent sediments deposited before regional European settlement. The 2005 mean epilimnetic TP and range of observed TP values are listed for all ten sites. The dissimilarity coefficient (DC) is calculated as the squared chi-squared distance between a fossil sample and its nearest modern analog among the 76 lakes in the logTP transfer function. A minimum dissimilarity coefficient (DC) score of less than 0.4067 (the first percentile of distance distributions among the modern samples), 0.6699 (the fifth percentile), and 0.8598 (the tenth percentile) identified a fossil sample with a very good, good, or poor modern analogue, respectively.

Site	Site/core depth	2005 observed mean TP	2005 observed TP range	DI-TP	DC	Modern analogue
	cm	ppb	ppb	ppb	-	-
Spring Park	Spring Pk (surf)	19	16-22	26.9	-	-
	Spring2	-	16-22	24.2	0.6896	G
	Sprin147	-	-	31.0	0.7994	P
	Sprin152	-	-	24.1	0.8623	P
St. Albans	St. Albans (surf)	18	13-22	31.1	-	-
	StAlb2	-	13-22	30.6	0.5185	G
	StAlb50	-	-	21.7	0.615	G
	StAlb55	-	-	21.7	0.6027	G
Stubbs Bay	Stubbs (surf)	79	58-101	53.5	-	-
	Stubbs2	-	58-101	51.6	0.5202	G
	Stubb145	-	-	38.7	0.7549	P
	Stubb150	-	-	37.7	0.6869	P
Wasserman	Wasserman (surf)	84	64-107	80.8	-	-
	Wasser2	-	64-107	86.8	0.302	VG

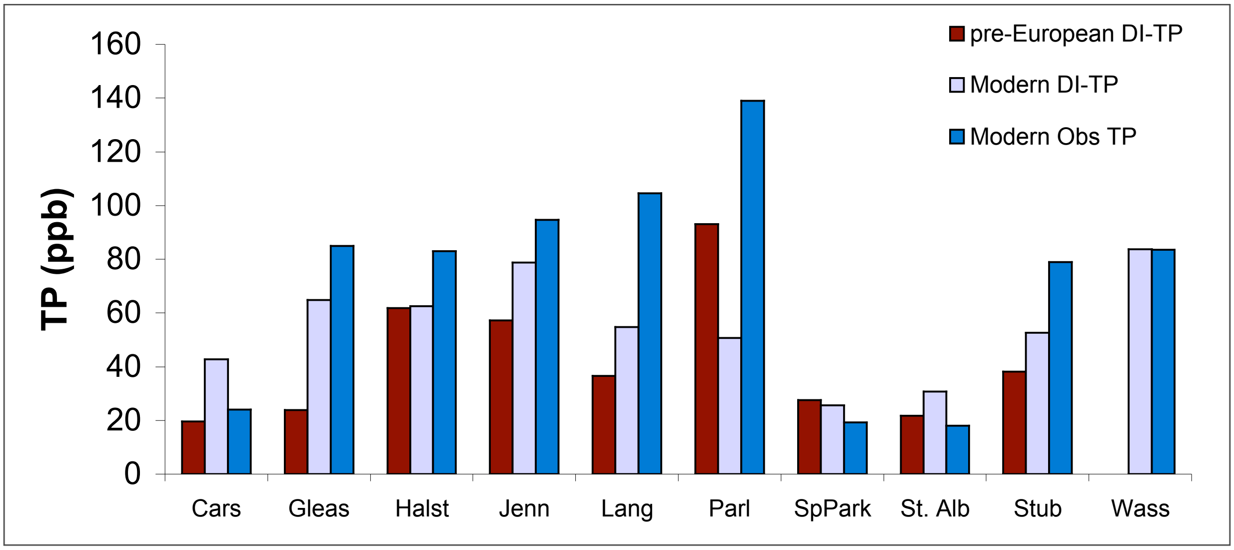


Figure 3. Histogram comparing pre-European diatom-inferred TP (DI-TP) with modern DI-TP and observed annual mean TP for ten lakes and bays in the Lake Minnetonka watershed.

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Dr. Lorin Hatch (MCWD) coordinated collection and analysis of environmental and physical data for the 10 lakes or bays in the Lake Minnetonka watershed in 2005. Dr. Shawn Schottler (SCWRS) provided ^{210}Pb gamma analysis. Erin Mortenson (SCWRS) prepared samples for gamma analysis. Dr. Norman Andresen assisted with microscopical analyses. The University of Minnesota's Limnological Research Center and Anders Noren are acknowledged for magnetics logging and core scanning.

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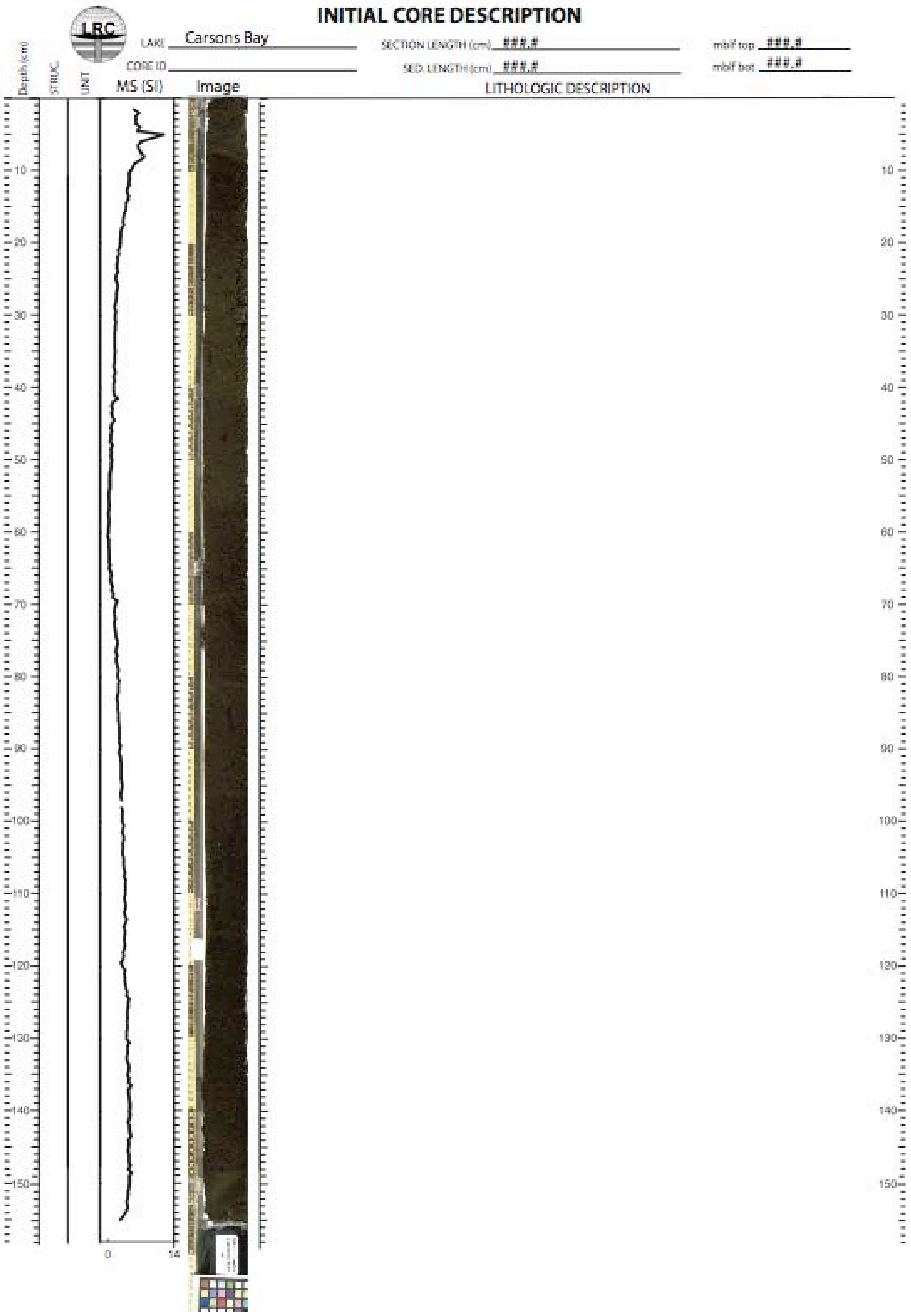
APPENDIX 1-CORE SCANS AND MAGNETICS LOGGING,



INITIAL CORE DESCRIPTION

LAKE Carsons Bay

CORE ID

SECTION LENGTH (cm) ###.#

SED. LENGTH (cm) ###.#

mblf top ###.#

mblf bot ###.#

Figure A-1. Magnetic susceptibility and core scan, Carsons Bay core. Field extruded to 49 cm.

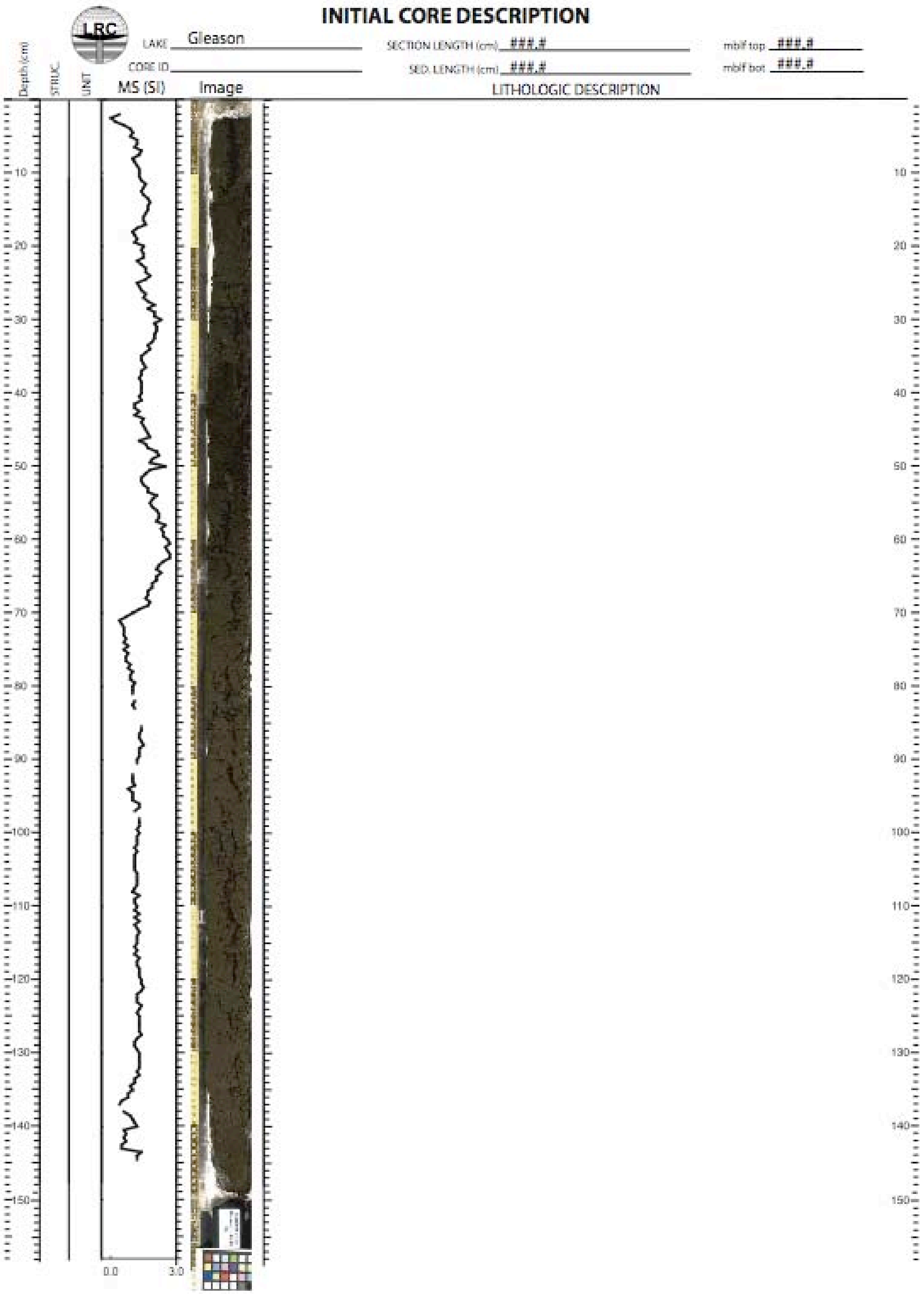


Figure A-2. Magnetic susceptibility and core scan, Gleason Lake core. Field extruded to 44 cm.

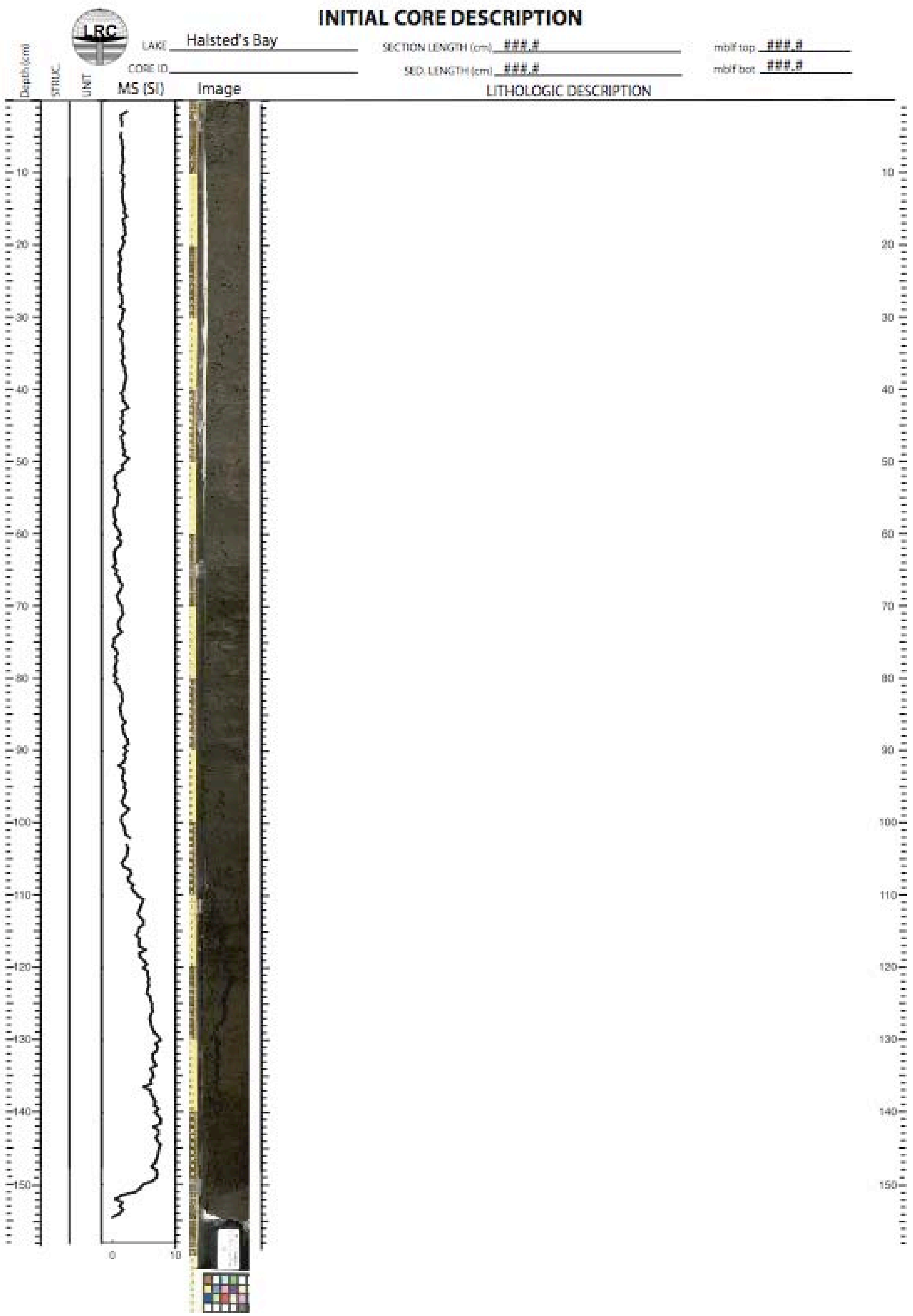


Figure A-3. Magnetic susceptibility and core scan, Halsteds Bay core. Field extruded to 40 cm.

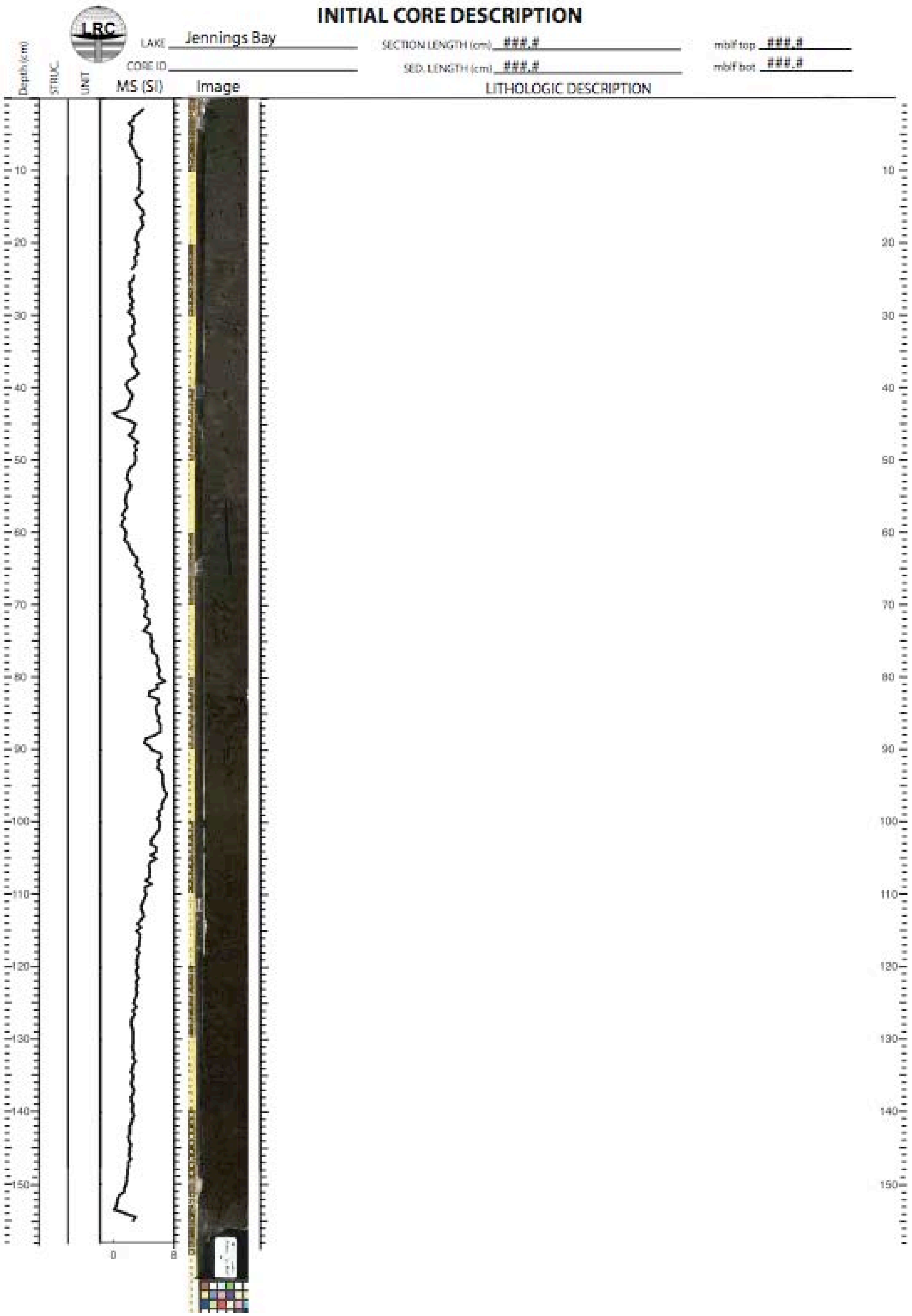


Figure A-4. Magnetic susceptibility and core scan, Jennings Bay core. Field extruded to 40 cm.

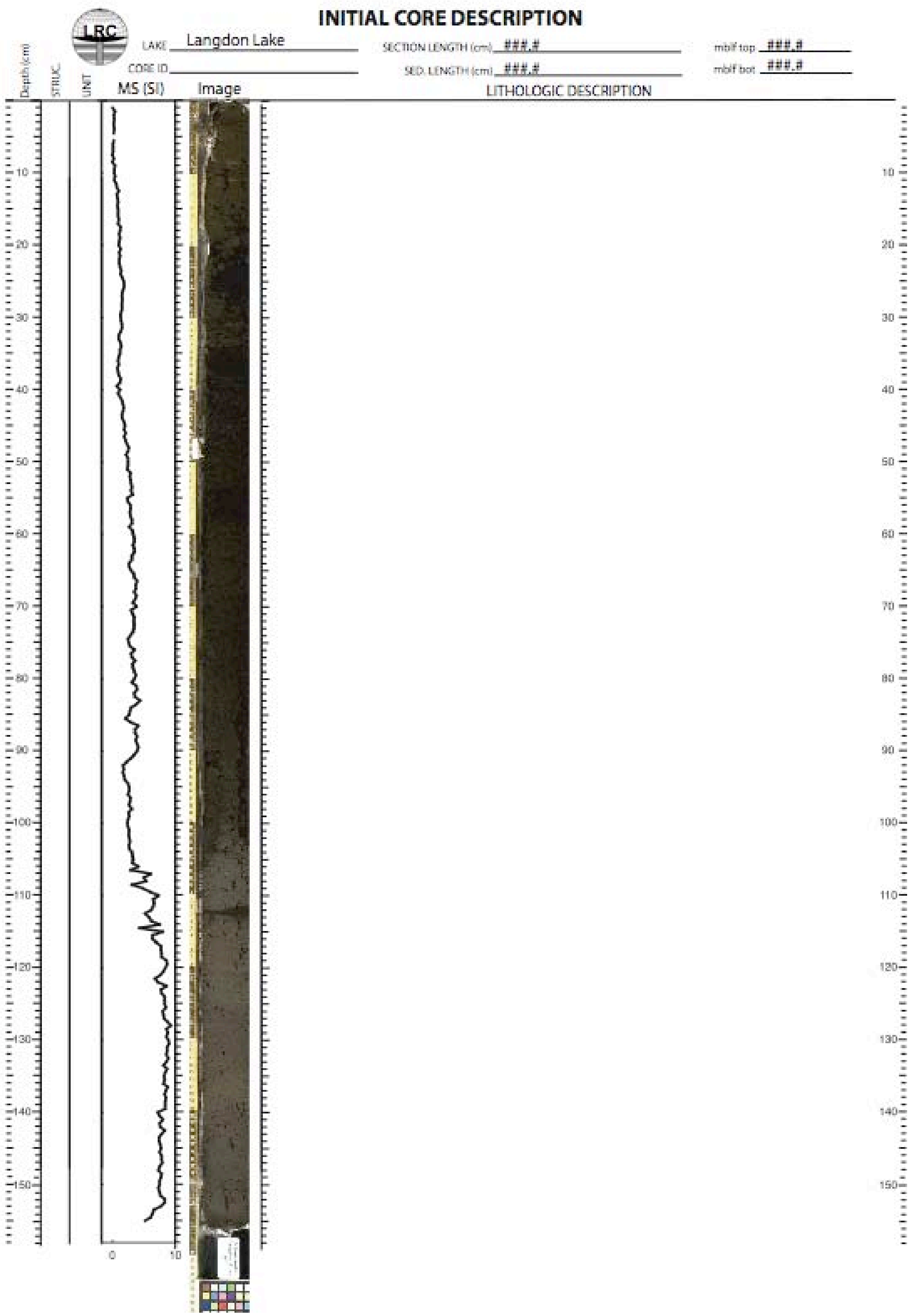


Figure A-5. Magnetic susceptibility and core scan, Langdon Lake core. Field extruded to 54 cm.

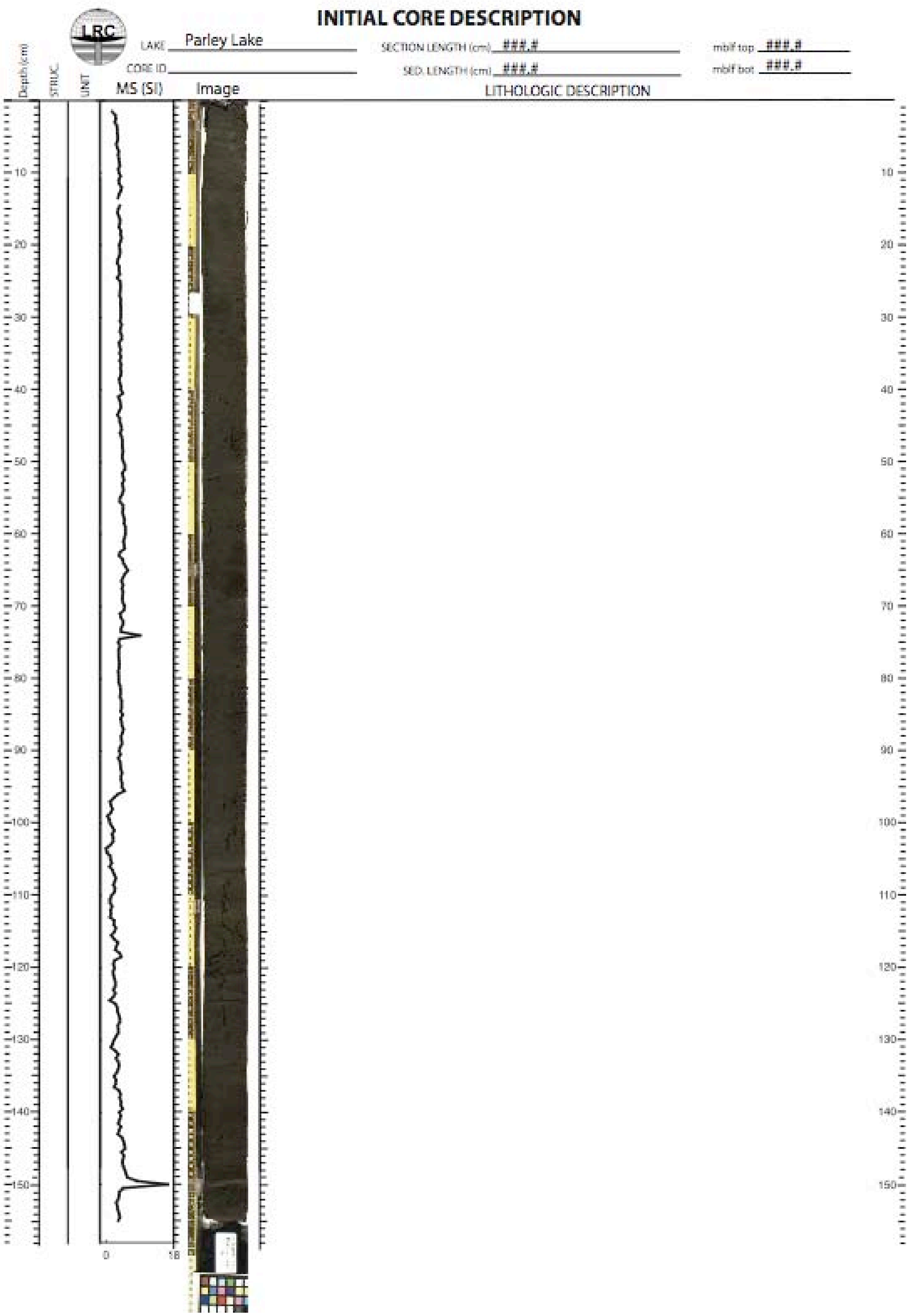


Figure A-6. Magnetic susceptibility and core scan, Parley Lake core. Field extruded to 36 cm.

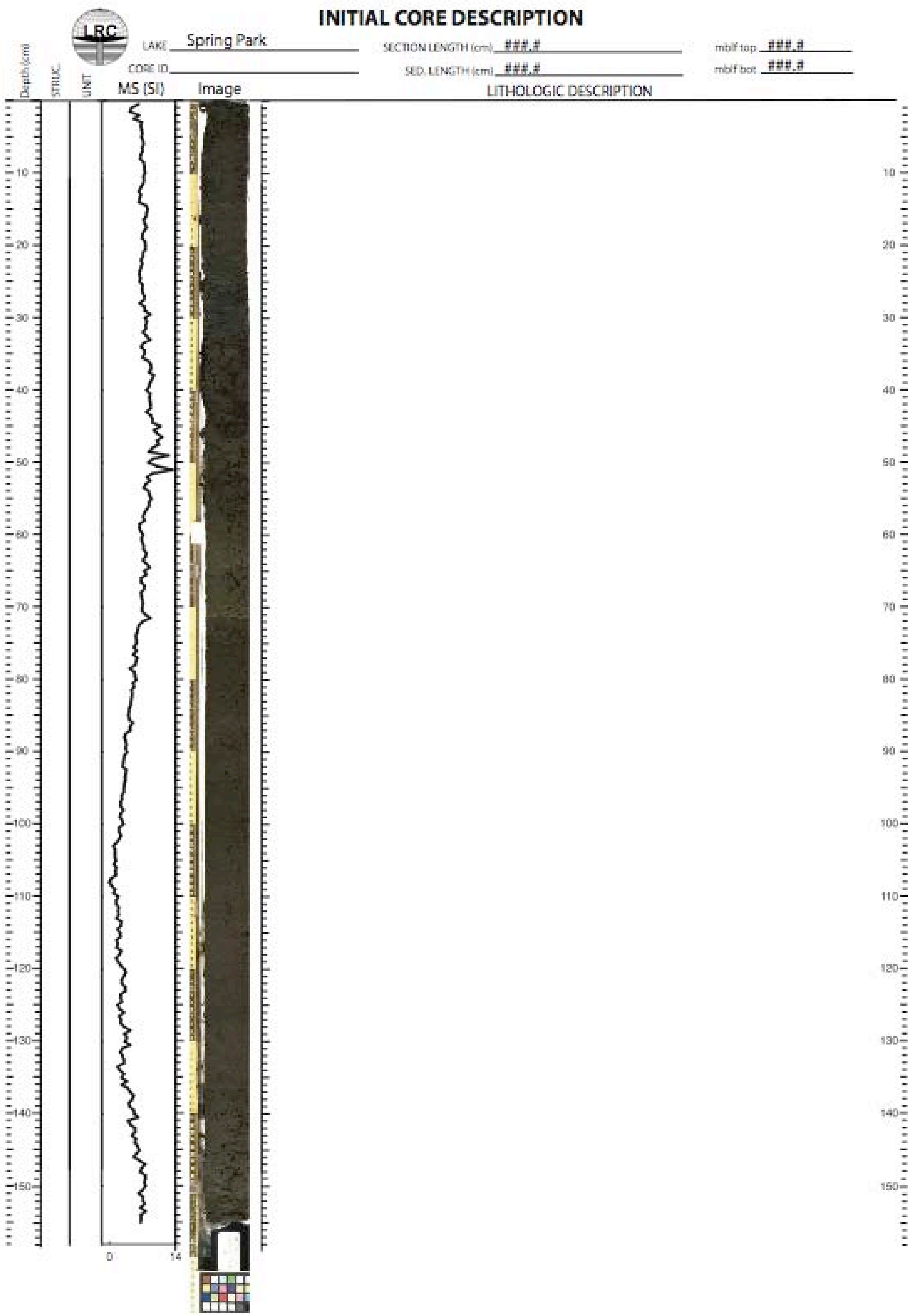


Figure A-7. Magnetic susceptibility and core scan, Spring Park Bay core. Field extruded to 40 cm.

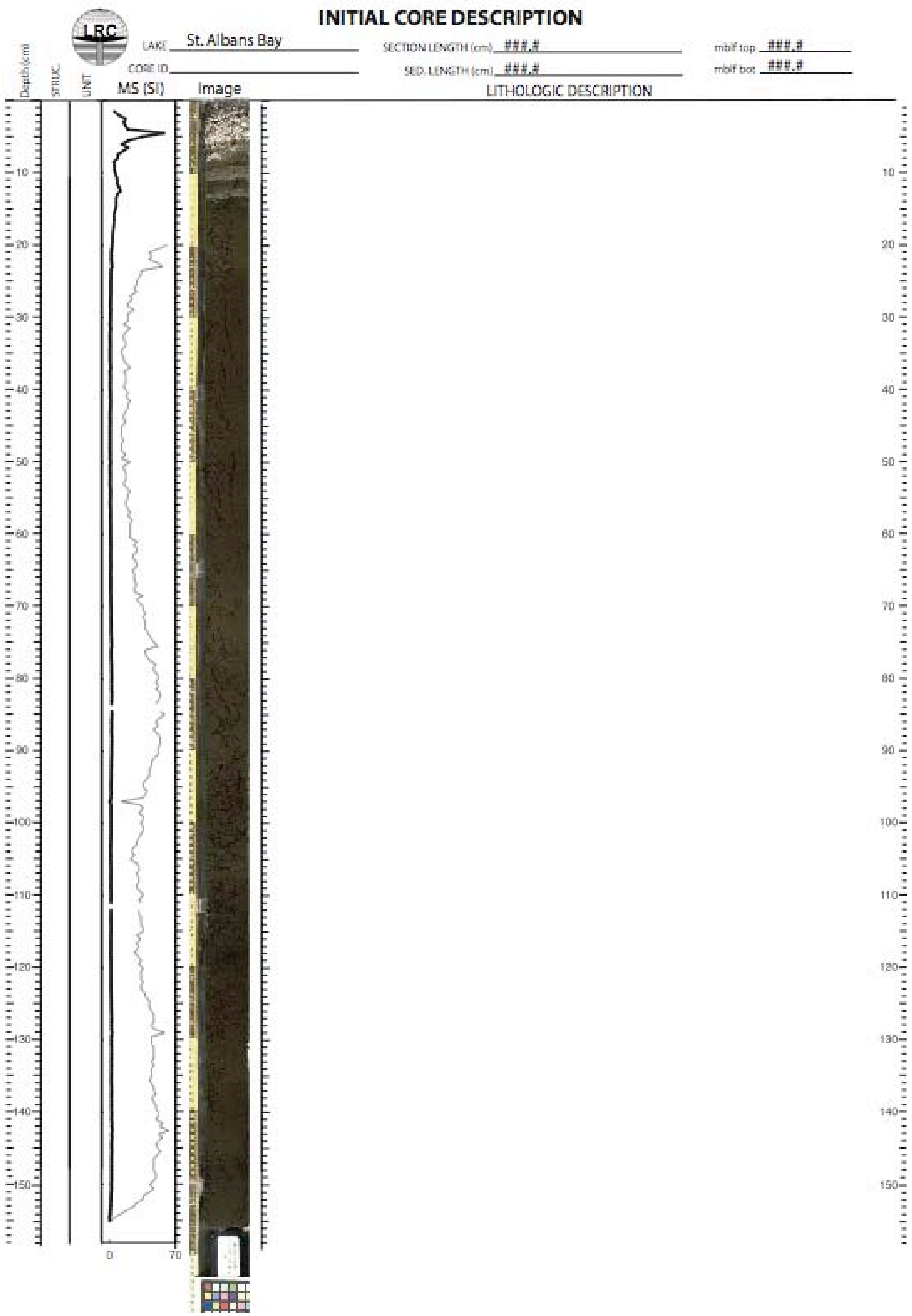
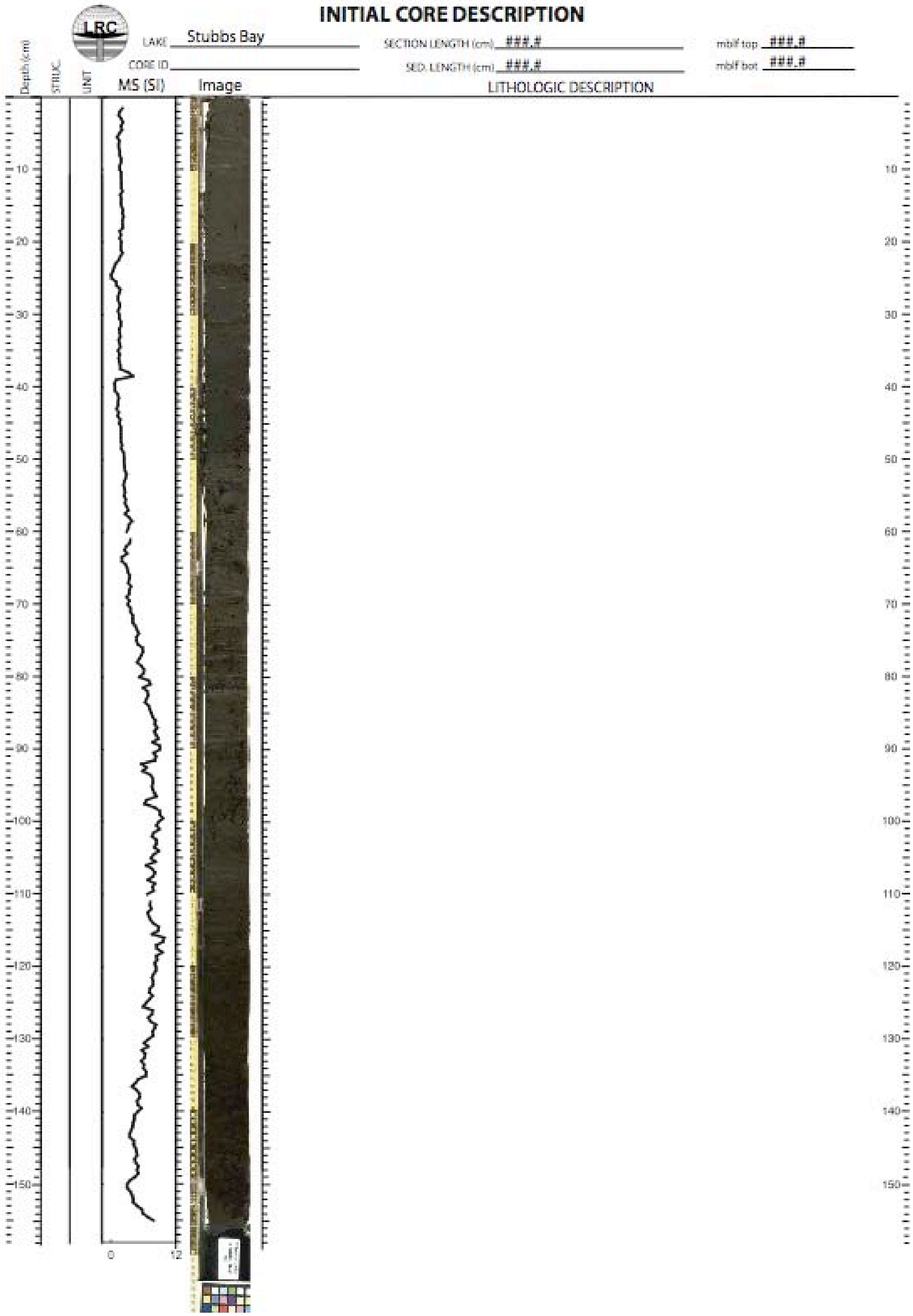


Figure A-8. Magnetic susceptibility and core scan, St. Albans Bay core. Field extruded to 43 cm.



INITIAL CORE DESCRIPTION

LAKE Stubbs Bay

CORE ID

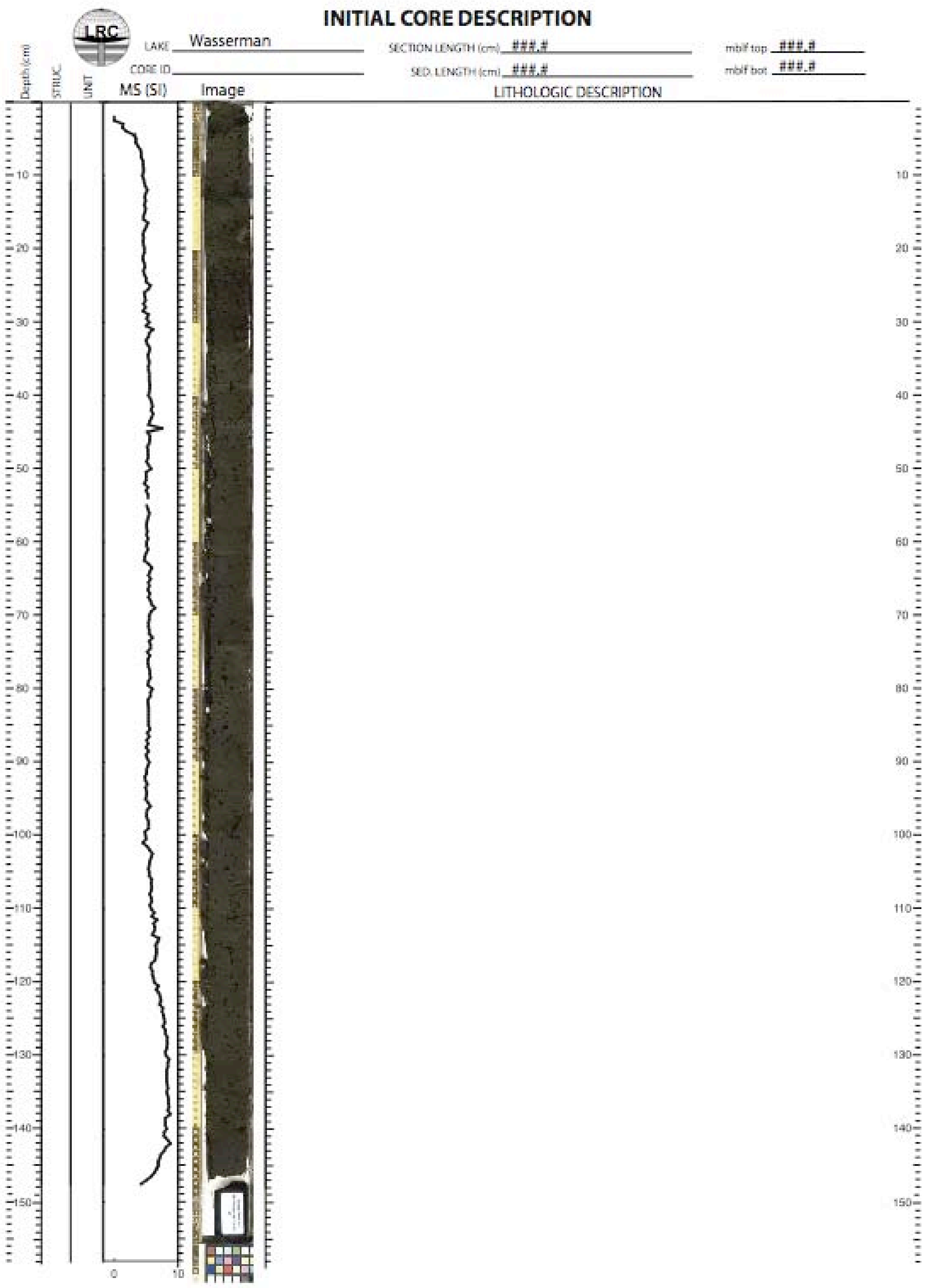
SECTION LENGTH (cm) ###.#

SED. LENGTH (cm) ###.#

mblf top ###.#

mblf bot ###.#

Figure A-9. Magnetic susceptibility and core scan, Stubbs Bay core. Field extruded to 36 cm.



INITIAL CORE DESCRIPTION

LAKE Wasserman

CORE ID

SECTION LENGTH (cm) ###.#

SED. LENGTH (cm) ###.#

mblf top ###.#

mblf bot ###.#

Figure A-10. Magnetic susceptibility and core scan, Wasserman Lake core. Field extruded to 28 cm.