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Project Title: Mammoth Crystal Springs Sediment Core Collection and Analyses, Sylvan Pass Area, Yellowstone National Park

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PROJECT SUMMARY

Sediment cores collected from Mammoth Crystal Springs Pond on the east side of Sylvan Pass were analyzed to characterize the uppermost clay unit and compare it with underlying sediments. The pond formed about 1200 cal yr ago and has been a shallow lacustrine/fluvial feature for most of its history. The uppermost clay unit is unique in the sedimentary history of the pond. One dating method indicates that the clay unit is younger than AD 1963, and another dating method more precisely places the onset of clay deposition in AD 1985 $\pm$ 6 years. The mineralogy of the uppermost clay unit was compared with other fine-grained sediments and found to be most similar to that of fine-grained sediments from gravel crushing operations and debris flow sediments at Sylvan Pass. Diatom analysis revealed small changes in aquatic biota with the deposition of the uppermost clay unit, including an increase in species that are adapted to disturbance.

INTRODUCTION

Mammoth Crystal Springs Pond (MCSP) is a small body of water about 100 m long and 50 m wide, fed by several springs emanating from talus on its west side. The site is surrounded by subalpine conifer forest that includes *Abies lasiocarpa*, *Picea engelmannii,* and *Pinus albicaulis*. The pond is bound on the south side by a large outcrop of Absaroka volcanics and on the west and north side by talus deposits. The springs feeding the pond come from a groundwater watershed that encompasses Sylvan Pass and areas to the south and west (See Fig.1 for site information). High water turbidity was reported in 2004, and the source was traced to light gray fine-grained sediments introduced from the springs (Heasler and Jaworowski, 2005). These fine-grained sediments coated the rock surfaces of the pond and caused turbidity downstream in Middle Creek in 2004 and 2005.

Our objective was to address the following questions: Is the input of fine-grained sediments into MCS a recent phenomenon, an episodic phenomenon that has also occurred in the past, or a persistent process that has taken place over centuries or millennia? Has the accumulation of the fine-grained sediments altered the limnology of MCSP, based on changes in the diatom flora?

To this end, sediment cores were collected from Mammoth Crystal Spring in 2006 and 2007 by researchers from Montana State University (MSU), University of Nebraska, and

University of Minnesota. Our task was to characterize the sedimentary history of the site, and in particular the source and age of the light gray fine-grained sediments. Description of the sediment cores, determination of the age of the site and the initiation of fine-grained sediment deposition, and an assessment of the paleolimnology were undertaken to address these questions.

The project was broken into two phases:

Phase 1: Collection of sediment cores at several locations in MCSP

Phase 2: Characterization of the sediments, including

1. Detailed core description, photodocumentation of cores, and examination of magnetic susceptibility.
2. Characterization of the uppermost fine-grained sediments from the core and comparison with other fine-grained lithologic units in the Sylvan Pass region, which might be its source.
3. Radiometric dating of the sediments to determine the age of the site and the uppermost light gray fine-grained sediment.
4. Diatom analysis of core material to evaluate whether or not there were changes in biological species composition, nutrient status, or other water-chemistry variables over the period of deposition. This part of the project was undertaken by Dr. Sherilyn Fritz and Brandi Bracht at the University of Nebraska.

METHODS

Field work

Field work was conducted in June 2006 and 2007. Cores were retrieved from an anchored floating platform that was moved to different locations within the pond. Long cores, short cores, and gravity cores were taken to provide sufficient material to address the objectives.

Long cores (MCSP06E, MCSP06F and MCSP06E) were taken in three different parts of the basin with a 5-cm-diameter modified Livingstone square-rod piston sampler (Wright et al., 1983). Core recovery was determined by the stiffness and coherency of the sediments and represented the deepest penetration possible with a hand-operated Livingstone sampler. The core segments obtained during a coring drive were extruded, measured and described in the field. The uppermost 15-20 cm of the long cores was loosely consolidated, and this material was collected and stored in plastic bags. The stiffer sediment below that depth was extruded at the site, wrapped in cellophane and aluminum foil, and transported from the field in tightly packed wooden boxes. These cores were used for stratigraphic descriptions and AMS radiocarbon dating.

A short core (MCSP06D) was recovered using a 7.5-cm-diameter Klein piston corer and extruded into plastic bags at 1-cm intervals. This core obtained the sediment-water interface intact and was used for lithologic and diatom analyses and ^{210}Pb age determinations. Another short core (MCSP07A) was taken near the coring site of MCSP06D to provide additional material. This core confirmed the stratigraphy of MCSP06D and was not analyzed further.

Klein gravity cores were obtained in three places in the basin to accurately determine the depth of the sediment-water interface and to collect the upper 15-20 cm of sediment in other locations. The cores were subsampled in the field into plastic bags at 2-cm intervals, but the sediments have not been analyzed further.

All samples and cores were transported to the MSU Paleoecology Lab, and materials have been kept refrigerated for the remainder of the study.

Lithologic analyses

Cores were described in the field initially and taken back to MSU for further examination and analysis.

Core MCSP06F, the longest core taken, was split longitudinally, and the lithology was carefully described. Photographs of the split cores were taken to record lithologic variation and location of sub-samples taken from the core. Color determinations were based on the Munsell soil color chart (2000) under visible light.

Magnetic susceptibility was measured on MSCP06F to estimate the relative input of clastic ferromagnetic minerals. Variations in magnetic susceptibility can provide evidence of changes in grain size and mineralogy that are used to described allochthonous sediment inputs related to erosion, fire, and lake-level changes (Gedye et al., 2000). A Bartington Magnetic Susceptibility core logging sensor was used to measure the magnetic susceptibility of the intact cores, and a Bartington MS cupcoil sensor was used to measure two representative samples (1-2 cm and 10-11 cm depths) from loosely consolidated gray clay unit in the top 18 cm of the core.

Chronology

Three dating approaches were used to gain information about the age and sedimentation history of MCSP:

Twenty-five samples from core MCSP06D were submitted for ^{210}Pb and ^{137}Cs determinations to Dr. James Budahn of the US Geological Survey in Denver. Samples of 24 ml volume were dried for 24 hours at 90ºC, and dry weight was calculated. ^{210}Pb, with a half-life of 22.3 years, is a widely used chronometer for the last century, especially in studies of recent sedimentation rates. ^{210}Po activity (the grand-daughter of ^{210}Pb) is actually measured in this procedure (see Results). The optimal material for ^{210}Pb is undisturbed sediments (e.g. low energy lake sediments) under-going a constant rate of deposition. Models that calculate ^{210}Pb dating assumes no mixing or disturbance of the particle settling of the sediment. Calculated ages greater than 60-100 years should be treated with caution because counting errors and small variations in the background ^{210}Po can cause large changes in the age estimates (http://www.flettresearch.ca).

^{137}Cs, with a half-life of 30.3 years, is a thermonuclear byproduct. Its presence is directly related to the atmospheric testing of nuclear devices during the late 1950s and early 1960's. A ^{137}Cs provides an important time-stratigraphic marker for comparison with the ^{210}Pb results.

A piece of wood at the base (230.5 cm depth) of the core was submitted to Lawrence Livermore National Laboratory for accelerated mass spectrometry (AMS) ^{14}C dating.

Clay mineralogy

X-ray powder diffraction (XRD) analysis was run on the light gray fine-grained lithology unit at the top of sediment cores.. Similar analysis was performed on fine-grained sediment samples from four distinct provinces in and near Sylvan Pass. These samples were provided by Hank Heasler (Yellowstone Center for Resources YNP) for comparison with the Mammoth Crystal Springs Pond uppermost clay unit.

Samples from core MSCP6D were prepared using the millipore filter transfer method (Moore and Reynolds, 1997; p. 216). Subsequently, ethylene glycol solvation (Moore and Reynolds, 1997; p. 224) was undertaken on each sample to enable more highly resolved identification of the clay components. Prepared slides were scanned on a Scintag X-1 diffractometer at 2 degrees/minute over a range of 3 to 73 degrees two theta.

Diatom analysis

Samples for diatom analysis were processed from 8 samples in core MCSP6D (0-1, 10-11, 15-16, 20-21, 25-26, 26-27, 30-31, 35-36 cm depth) and 13 samples in core MCSP6F (19-20, 22.5-23.5, 26-27, 28.5-29.5, 31.5-32.5, 38-39, 46.5-47.5, 53.5-54.5, 66-67, 95.5-96.5, 110-111, 180-181, 198-199 cm depth). The two cores overlap stratigraphically, with short core MCSP6D providing an assessment of the most recent period of sediment deposition.

Samples for diatom analysis were treated with 10% hydrochloric acid and cold hydrogen peroxide to respectively remove carbonates and organic matter and then were rinsed to remove oxidation by-products. Prepared samples were dried onto coverslips, and the coverslips were mounted onto slides with Naphrax. Species were identified on a Zeiss Axioskop 2 microscope with a 1000x (N.A. = 1.40) oil immersion objective. A minimum of 300 diatom valves were counted on each slide. Diatom abundance in each sample is expressed as a percent of the total diatom count.

RESULTS AND DISCUSSION

Site and core descriptions

In June 2006, water depth at Mammoth Crystal Springs Pond was <95 cm. The pond was dammed by logs at its eastern outlet, the water was clear and cold, and the inflow came from springs in talus material along the south and southwest shore and subsurface. Submerged logs and springs were evident throughout the basin which limited possible coring sites. The residence time of water in the lake seemed very short, although measurements were not taken by our group.

The long sediment cores were obtained within a meter radius of each other in the eastern half of the lake in 75 cm of water. Core recovery was 230.5 cm for MCSP06E, 99 cm for MCSP06F, and 39 cm for MCSP06G (See Fig. 2 for core locations). A 36-cm-long short core (MCSP06D) was recovered in the western half of the basin for the ^{210}Pb and diatom analyses. Three gravity cores (MCSP06A, MSCP06B, and MSCP06C) measuring 22, 16, and 27 cm in length, respectively, were collected in approximately 88 cm water depth to capture the sediment-water interface in different parts of the basin. MCSP06A was taken in the western part, MCSP06B was taken in the center of the basin, and MCSP06C was collected in the eastern part near the basin. It was difficult to avoid submerged logs during coring, and several efforts to retrieve sediment were made before these cores were obtained (Fig. 3 for field work pictures).

The lithologic stratigraphy of all cores was generally the same (see Fig. 4 for field and lab descriptions). Most notable for this report was the presence of a light gray fine-grained sedimentary unit at the tops of all cores, hereafter referred to as the uppermost clay unit (color: GLEY1/7/N). The unit ranged between 12 and 24 cm in thickness in the 2006 cores taken across the basin. In the 2007 core, MSCP07A, the unit was 37 cm thick. This distinctive clay unit was unique in the sedimentary record in that it was not found at greater depths in any of the cores. Magnetic susceptibility values of the upper unit ranged from 39 to 120 10^{-6} CGS units, which were low compared to values deeper in the core (Fig. 5). The cumulative dry weight accumulation (Fig. 6) indicates a change in sediment accumulation rate at 22 cm depth, consistent with the beginning of the uppermost clay unit.

In general, sediments below the uppermost clay unit ranged from well sorted sand to silty clay, and multiple fining upward sequences of sand grading to silt and silty clay were noted. Plant detrital material was found throughout the core, except in the uppermost clay unit. The core descriptions that follow are from MSCP06F, the longest of the long cores, and they start at the bottom of the core and go upwards. Figure 3 shows descriptions based on the field notes and Figure 4 illustrates the lithology of core MSCP06F:

From 228 to 222 cm in depth, the core consisted of dense woody debris in a reddish-brown (5YR4/4) matrix of sand. A fragment of wood was taken from this unit for AMS radiocarbon dating. A short fining upward interval was present between 222 and 219 cm depth, where very dark gray (GLEY1N/3) fine sand graded upward to very dark gray (GLEY1N/3) silt. Between 219 and 215 cm depth was a unit of dark greenish gray (10Y4/1) clay with abundant wood fragments and organic detritus. From 215 to 213.3 cm depth, the core was composed of dense black organic material. From 213.5 to 211 cm depth was is a dark greenish-gray (5GY4/1) clay layer with organic detritus. It was overlain by another fining upward sequence of very dark gray (GLEY1N/3) medium subrounded sand grading upward to very dark gray (GLEY1N/3) silt between 211 and 203.5 cm depth. From 198.5 to 203.5 cm depth was a unit of dark greenish-gray (5GY4/1) clay with leafy plant organic detritus, overlain by a thin unit (198.5 to 196.5 cm depth) of very dark gray (GLEY1N/3) fine sand. From 196.5 to 187 cm depth was another fining upward sequence in which very dark gray (GLEY1N/3) subrounded medium-coarse sand graded to very dark gray (GLEY1N/3) fine sand. From 187 to 174 cm depth was very dark gray (GLEY1N/3) subrounded medium-coarse sand, with no organic material. The interval from 174-144 cm depth was a sand unit that lack cohesion and was not recovered (Livingstone corers are not designed to retrieve unconsolidated sand.)

From 144 to 97.5 cm depth was a thick fining upward sequence beginning with very dark gray (GLEY1N/3) subrounded medium-coarse sand that graded to very dark gray (GLEY1N/3) silt. The unit between 97.5 and 94 cm depth contained very dark gray (GLEY1N/3) clay with organic detritus (leafy plant material). The interval from 94 to 74 cm depth was not recovered in Core MCSP06F, but equivalent depths from MSCP06E indicate that the sediment consisted of medium sand grading upward to silty clay

(GLEY1N/3). Between 74 and 60.5 cm depth was a fining upward sequence in which dark reddish brown (2.5YR3/3) fine sand graded upward to dark reddish brown (2.5YR3/3) fine silt. Plant and wood fragments were abundant in this unit. The unit from 60.5 to 55 cm depth consisted of dark brown (7.5YR2.5/2) silt with scattered organic detritus (leafy plant material). It was overlain by a thin unit (55 to 54.2 cm depth) of dark reddish brown (2.5YR3/3) silt. A dense layer of leafy plant detritus and wood fragments was present between 54.2 and 53.5 cm depth, with small amount of dark greenish-gray (5GY4/1) silt. The interval from 53.5 to 48.5 cm depth featured a fining upward sequence of dark greenish-gray (5GY4/1) fine sand grading to greenish-gray (5GY4/1) fine silt. From 48.5 to 45.5 cm depth was dark greenish-gray fine sand unit that graded upward to dark greenish-gray (5GY4/1) clay. From 45.5 to 32.4 cm depth, a dark gray (GLEY1N/3) fine sand unit graded upward to dark gray (GLEY1N/3) clay. At 32.4 to 31.5 cm depth, a band of olive-gray (5Y4/2) clay was present. From 31.5-28.5 cm depth was silty clay of dark greenish-gray (5GY4/1) to very dark gray (GLEY1N/3) color. From 28.5 to 22.5 cm depth, the lithology consisted of dark yellowish brown (10YR/3/6) silt to fine-grained sand. From 22.5 cm to the mud-water interface was unconsolidated light gray fine-grained sediments (GLEY1/7N), the so-called uppermost clay unit. As stated above, the uppermost 12 to 37 cm of sediment in all the cores consisted of this distinctive light gray clay unit. This lithologic unit was unique in that a similar lithology was not present at greater depths.

Magnetic susceptibility values below 74 cm depth ranged from 2.4 to 569 x 10^{-6} cgs units. Between 74 and 22.5 cm depth, values were ranged from 52.9 to 966.6 x 10^{-6} cgs units. The uppermost light gray clay by contrast had low magnetic susceptibility values (39 to 120 10^{-6} cgs units), which probably reflects the low sediment magnetism of clay-sized sediments (Thompson and Oldfield, 1986).

Chronology

An AMS radiocarbon date of 1275 + 40 ^{14}C yr BP (CAMS-128994) on a wood fragment was obtained at the base of the core MCSP06F (228 cm depth) had a calibrated age of 1166 - 1290 cal yr BP (CALIB 5.02; Stuiver et al., 1998, 2005). The median age of the calibrated date is 1218 cal yr BP. The sedimentation rate (0.19 cm/yr for the entire core; 0.17 cm/yr if the upper clay is not included)) is high compared with other small lakes that Whitlock has cored in Yellowstone National Park. For example, six lakes in the region had sedimentation rates between 0.0002 and 0.09 cm/yr in the upper meter of sediment (Whitlock, 1993). This comparison suggests a significant allochthonous or nonlimnologic source for the sediments at MCSP. Tourist descriptions of Mammoth Crystal Springs in 1901 and 1904 make no reference to the pond, which suggests that the pond itself may be a geologically recent feature (H. Heasler, pers. comm., 2006).

Results of the ^{137}Cs and ^{210}Pb dating are shown in Table 1. High values of ^{137}Cs occurred between 26 and 32 cm depth, with highest values in the 28-29 cm depth sample. The world-wide fallout of ^{137}Cs associated with the nuclear weapon tests during the 1950s and 1960s, and the highest measured value is result of the maximum fluxes between 1962 and 1965. Due to difficulties in sample and sampling resolution the peak value is usually assumed be correspond to AD 1963 $\pm$ 2 years (Appleby, 2001). From this information, we conclude that the deposition of uppermost clay unit (0-22.5 cm depth) began after AD 1963.

The highly variable sediment accumulation rates implied by the sediments at MCSP is more typical of a man-made reservoir with high flow-through and mixing and low levels of unsupported lead (Appleby, 2001). As a result, the site is not ideal for this dating method. Nonetheless, a few observations can be made: The lowest activity of ^{210}Po (35 cm depth) (Fig. 7A) marks the lowest depth that ^{210}Pb dating is possible (ca. 100 years, approx. 5 half lives), and it lies well below the depth of the uppermost clay unit. Cumulative dry-weight sediment accumulation suggests an increase in sedimentation rate at 22 cm depth, and this matches fluctuations in the ^{210}Po profile that suggest faster sedimentation rates in the uppermost 25 cm and especially in the uppermost 14 cm of core MCSP06D (Fig. 7A). Dates were calculated with the constant rate supply (CRS) model, with confidence intervals around each sample calculated by first-order error analysis of the analytical uncertainty (Binford, 1990; Appleby, 2001). The age model was based on a smoothing spline using estimated ages at each sample depth. Error estimates for the chronology are based on 1000 random samples of sample ages, incorporating their variability (Fig. 7B, gray shading). With this method, the base of the uppermost clay unit (22.5 cm depth) is ca. AD 1985 $\pm$ 6 (2 sd) years. This age determination is probably the best that can be achieved at this site with this particular method. Using a slightly different interpolation method (provided by J. Budahn), produced an age of AD 1983 (no specified error), which is consistent with these results. Thus, the sedimentation rate of the clay layer (conservatively: 0.52-1.07 cm/yr) is several times higher than that of the underlying sediments, attesting to its different origin and character.

X-ray Diffraction

Five samples were analyzed using X-ray powder diffraction, including the uppermost clay at MCSP06 (see Fig. 1 for sample location):

- West End Area 4 fine-grained sediments (WEP04) and East End Area 4 fine-grained sediments (EEA406): These samples were collected from the discharge resulting from the 2005 crusher operations on Sylvan Pass. The sediments were fine-grained, white to gray in color and collected on June 21, 2006.

- Debris flow sediments (DFF04): Along the East Entrance Road, numerous landslides occurred as a result of the locally heavy rainfall on the evening of July 18, 2004. A detailed discussion of this mass wasting event was described in an internal National Park Service document (Jaworowski and Heasler, 2004). Light-colored andesitic lava flows and volcaniclastic rocks crop out in the area of Sylvan Pass. These volcanic rocks are prone to slow and fast mass wasting events. The intense precipitation of July 18th caused rill erosion in saturated ground at Sylvan Pass.

  These debris flows are fast moving slurries of mud-rich water and rock. Levees with coarse and angular rocks form along the edges of debris flows. When these debris flows stopped moving, they formed a toe consisting of angular clasts of volcanic rock within a muddy-brown matrix. On the East Entrance road, mud-rich, brown water still oozed from the rocky toes of these debris flows and flowed down the road even a day after the landslides. These sediments are typically unsorted and matrix-supported.

During Fall 2006, YNP geologists sampled fine sediments from the toe of a debris flow. This debris flow moved across the current East Entrance Road, continued to flow downslope and eventually stopped on the old East Entrance Road.

- Fine-grained glacial sediments (GF 06): During discussions with Dr. Kenneth Pierce (US Geological Survey geologist, emeritus), he recommended collecting representative "glacial fines" from the proglacial lake sediments along Clear Creek at stratigraphic section 21. The paleogeographical setting of these "glacial fines" is taken from a description of the Pinedale glaciation by Richmond and Pierce (1972)

  > *"Early in Pinedale time, valley glaciers descended from the high parts of the Absaroka Range southeast of the quadrangle and coalesced in the valley of the Yellowstone River into a single large glacier which flowed northwest into the basin of Yellowstone Lake. Here, the ice formed a center for snow accumulation and enlarged gradually, until it ultimately overflowed the crest of the Absaroka Range at altitudes of 10,000-10,500 feet. Evidence for this is preserved in valleys east of the lake where thick deposits of proglacial gravel and lake silt, formed in ponds dammed by ice downstream are overlain by clayey Pinedale till….."*

  According to Richmond and Pierce (1972), these fine-grained proglacial lake sediments occur along the Clear Creek drainage. Richmond and Pierce identified 25 feet of Pinedale till overlying 25 feet of proglacial lake silt (surficial geologic map unit "ppl") at stratigraphic section number 21. They describe the sediments as

  > *"Moderately compact greenish-gray to brown silt mapped along Clear Creek. Also noted in stratigraphic sections 2, 5, 9, and 21, beneath Pinedale till. Commonly poorly exposed, but indicated by seepage zone at top of lake silt and by landsliding of overlying units. Along Clear Creek, deposit is more than 25 feet thick and consists of a lower well-bedded sandy unit and an upper massive silt unit. Ice-rafted pebbles, including obsidian, common in upper part; material grades upward into clayey Pinedale till."*

  Since 1972, recent fires have burned the Clear Creek drainage making it easier to walk along Clear Creek and examine the surficial geology. On the 1972 surficial geologic map, this section of Clear Creek is mapped as fine grained alluvium (map unit "fa"). Underneath the fine-grained alluvium of Clear Creek, it was easy to see the proglacial lake sediments. YNP geologists noted ledges of the compact proglacial lake sediments at the base of the current terrace along Clear Creek.

  At stratigraphic section 21, YNP geologists found a good exposure of fine-grained lake sediments. During fall 2006, YNP geologists collected a sediment sample from the fine-grained, well-bedded sediments at the base of stratigraphic section 21. During collection, YNP geologists also noted the compact nature of these proglacial sediments.

- Mammoth Crystal Springs Pond clays (MCSP06 3-4): uppermost clay unit taken from short core MCSP06D at 3-4 cm depth.

The prepared slides of sediment revealed a distinct color difference for sample DFF04 when compared to the other four samples. XRD scans were plotted in degrees for WEP04, EEA406, GF06, DFF04, and MCSP06 3-4 and the results were stacked relative to one another (Fig. 8). Major peaks are labeled according to mineral and clay peak presence, after consultation with Dr. David Mogk (MSU Department of Earth Sciences). The smaller, unlabeled peaks correspond to lesser peaks of already-identified minerals of plagioclase and quartz.

The mineral composition of the samples was similar with the exception of GF06, which had a greater amount of quartz and lacked many of the clay peaks present in MCSP06 3-4 and the other samples. MCSP06 3-4 and GF06 were reanalyzed following ethylene glycol salvation to more closely compare the clay peaks between 3-15 degrees, where most clay peaks can be found (Fig. 9). GF06 showed low abundance of expansive clays and illite-muscovite minerals relative to MCSP06 3-4, which again suggested a different geologic source. These data suggest that the source of the uppermost clay unit from MCSP does not originate from the glacial fines provenance (GF06). It is more likely to have come from the same source as WEP04, EEA406, and DFF04. The color difference between DFF and MCSP06 3-4 suggests that DFF is not a primary source for the clay at MCSP.

Paleolimnology

Overall, the core sequences were dominated by benthic diatom taxa with broad ecological tolerances (Fig. 10). The dominant species are in a single diatom family, the Fragilariaceae (*Fragilaria constricta*, *Fragilaria leptostauron*, *Staurosirella pinnata*, *Staurosirella venter*, *Staurosira construens* and var. *pumila*). These species grow attached to substrates, including rocks, sand, and mud and are common in springs, as well as other freshwater aquatic habitats.

Diatom valves were severely dissolved in the uppermost clay unit in both cores (sample at 20-21 cm depth in core MCSP06D; samples at 19-20 cm, 26-27 cm, and 28.5-29.5 cm depth in core MCSP6F) and moderately dissolved in sediments above this (in samples 10-11 and 15-16 cm depth in core MCSP6D). The dissolution is a post-depositional process, likely resulting from ion exchange and low dissolved silica in the pore waters of the sediments.

The diatom flora showed limited evidence of change in species composition above the uppermost clay unit (Core MCSP6D). The abundances of *Fragilaria leptostauron* (at 10-11 cm depth) and *Staurosirella venter* (15-16 cm depth) are somewhat higher in two samples above the uppermost clay unit than elsewhere in the analyzed core sediments, but their abundance is likely higher, because the valves are heavily silicified and therefore robust and resistant to dissolution relative to some of the other species. The uppermost sample (0-1 cm depth, core MCSP6D), which represents modern conditions, is dominated by taxa present earlier in the record, but this sample also includes three species that are not present in prior times and together comprise ~20% of the flora: *Amphora pediculus, Cymbella cistula,* and *Encyonopsis microcephala*. *Amphora pediculus* and *Encyonopsis microcephala* are widely distributed and often increase following disturbance. *Cymbella cistula* is commonly an epiphyte (species attached to plants) and thus may indicate an increase or change in the macrophyte flora. Together the appearance of these species suggests a small change in the aquatic ecosystem during recent times.

CONCLUSIONS

Based on this study of sediment cores from MCSP, we conclude that the lake is a fairly recent geologic feature compared with most natural lakes in the GYE, which were created during deglaciation over 14,000 cal years ago. MCSP seems to have formed when logs, alluvium or colluvium dammed its eastern outlet <1215 cal yrs ago. Most of its sedimentary record suggests deposition in a fluvial or very shallow lacustrine system, with large amounts of allochthonous inorganic sediment input. The variable lithology ranging from silty and clay to well-sorted sand, the repeated fining upward of lithologic sequences, and the rapid sedimentation rates (average: 0.17 cm/yr) are consistent with this interpretation. The ubiquitous organic detrital material also attests to persistent input of terrestrial vegetation through surficial processes.

The uppermost clay unit is different from the underlying sedimentary units both in color and lithology, which suggests a different origin. The low magnetic susceptibility in the uppermost clay unit is consistent with its small grain size. The XRD data indicate a close affinity between the uppermost clay unit and samples taken at WWE and EEA on Sylvan Pass, but the exact source or transport mechanism by which such sediment was introduced to MCSP cannot be determined from these data.

Based on two dating methods, the uppermost clay unit is younger than AD 1963 and most likely younger than AD 1985. The sedimentation rate of the clay layer (conservatively: 0.52-1.07 cm/yr) is several times higher than that of the underlying sediments, attesting to its different origin and character.

The diatom assemblages of the uppermost clay unit showed minor differences from the assemblages obtained in lower sediments. The clay unit had higher abundance of robust, dissolution-resistant forms and three new diatom species were present. The ecology of these new species suggests an increase in disturbance and possibly in aquatic macrophytes.

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Table 1: Results from ^{210}Pb and ^{137}Cs age determinations from MCSP06D

INPUT DATA					^{137}Cs activity		^{210}Pb Ages			^{210}Pb Age Model			
Top depth (cm)	Bottom depth (cm)	^{210}Po Total Activity (DPM/g)	Error ^{210}Po ± 1 S.D. (DPM/g)	Dry / Wet Wt. (g/cm^3)	Top depth (cm)	Total Activity ^{137}Cs (dpm/g)	Top depth (cm)	Age (yr AD)	1 S.D. (yr)	Top depth (cm)	Age (yr AD)	Upper 95% CI (yr AD)	Lower 95% CI (yr AD)
0	1	19.33	0.50	0.0990	0	0.12	0	2006	1	0	2006	2007	2005
2	3	4.90	0.50	0.6150	2	0.04	2		2	1	2005	2008	2002
4	5	3.26	0.50	0.5060	4	0.05	4	2002	2	2	2004	2008	2000
6	7	4.49	0.50	0.4290	6	0.05	6	2002	2	3	2003	2006	2000
8	9	3.96	0.50	0.4400	8	0.11	8	2000	2	4	2002	2006	1999
10	11	3.47	0.50	0.4320	10	0.05	10	2000	2	5	2002	2005	1999
12	13	3.57	0.50	0.4180	12	0.05	12	1999	2	6	2002	2005	1998
14	15	8.75	0.50	0.3950	14	0.06	14	1997	2	7	2001	2004	1998
16	17	6.22	0.50	0.3720	16	0.06	16	1994	2	8	2001	2004	1997
18	19	7.33	0.50	0.3770	18	0.09	18	1991	2	9	2000	2003	1997
20	21	4.65	0.50	0.3960	20	0.06	20	1988	2	10	2000	2003	1996
22	23	6.07	0.50	0.4780	22	0.67	22	1985	3	11	1999	2002	1996
23	24	5.29	0.50	0.5950	23	0.69	23	1983	3	12	1999	2003	1995
24	25	5.81	0.50	0.5840	24	0.78	24	1981	3	13	1998	2002	1995
25	26	8.15	0.50	0.4110	25	0.75	25	1978	3	14	1997	2001	1993
26	27	14.20	0.50	0.3480	26	1.75	26	1975	3	15	1996	1999	1992
27	28	14.82	0.50	0.3690	27	1.99	27	1968	4	16	1994	1998	1990
28	29	8.85	0.50	0.4070	28	3.21*	28	1957	6	17	1992	1996	1989
29	30	6.82	0.50	0.4800	29	2.78	29	1949	8	18	1991	1995	1987
30	31	4.60	0.50	0.5470	30	1.78	30	1940	10	19	1989	1994	1985
31	32	4.41	0.50	0.7300	31	1.06	31	1933	12	20	1988	1993	1983
32	33	3.13	0.50	0.9970	32	0.43	32	1923	15	21	1987	1992	1981
33	34	4.45	0.50	1.0380	33	0.16	33	1917	15	22	1985	1991	1980
34	35	3.58	0.50	0.9510	34	0.02	34	1883	29	23	1983	1989	1978
35	36	2.35	0.50	0.9850	35					24	1981	1987	1975
										25	1978	1984	1972
										26	1975	1981	1968
										27	1968	1976	1960
										28	1957	1969	1945
										29	1948	1962	1934
										30	1940	1959	1921
										31	1933	1958	1911
										32	1923	1951	1894
										33	1916	1945	1886
										34	1883	1939	1832

* High ^{137}Cs value is assigned to AD 1963 ± 2 yrs (see text).

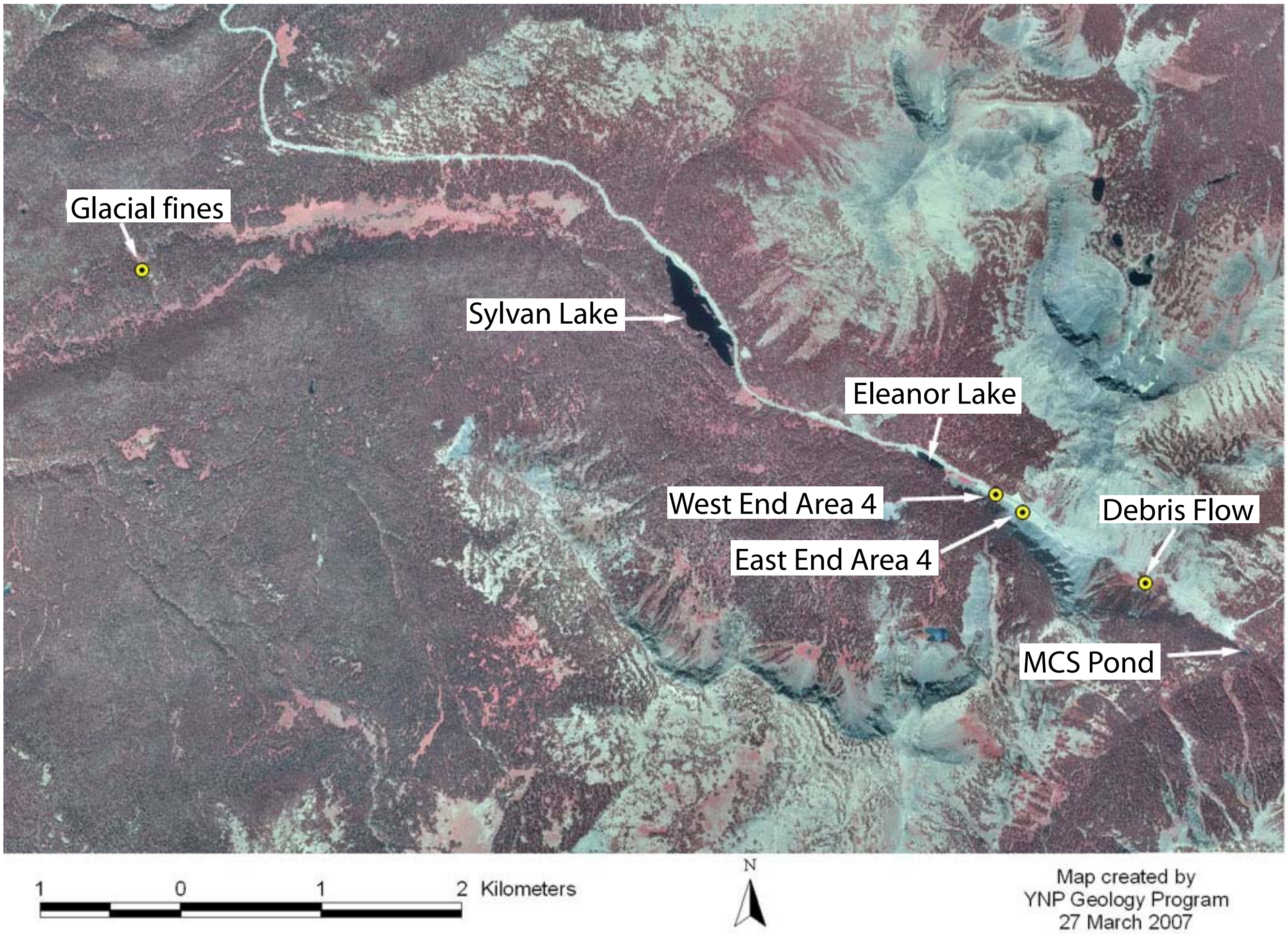

Figure 1. Study area including the location of Mammoth Crystal Springs Pond (MCSP) with repect to Sylvan Pass Road and other features described in text (photo provided by H. Heasler).

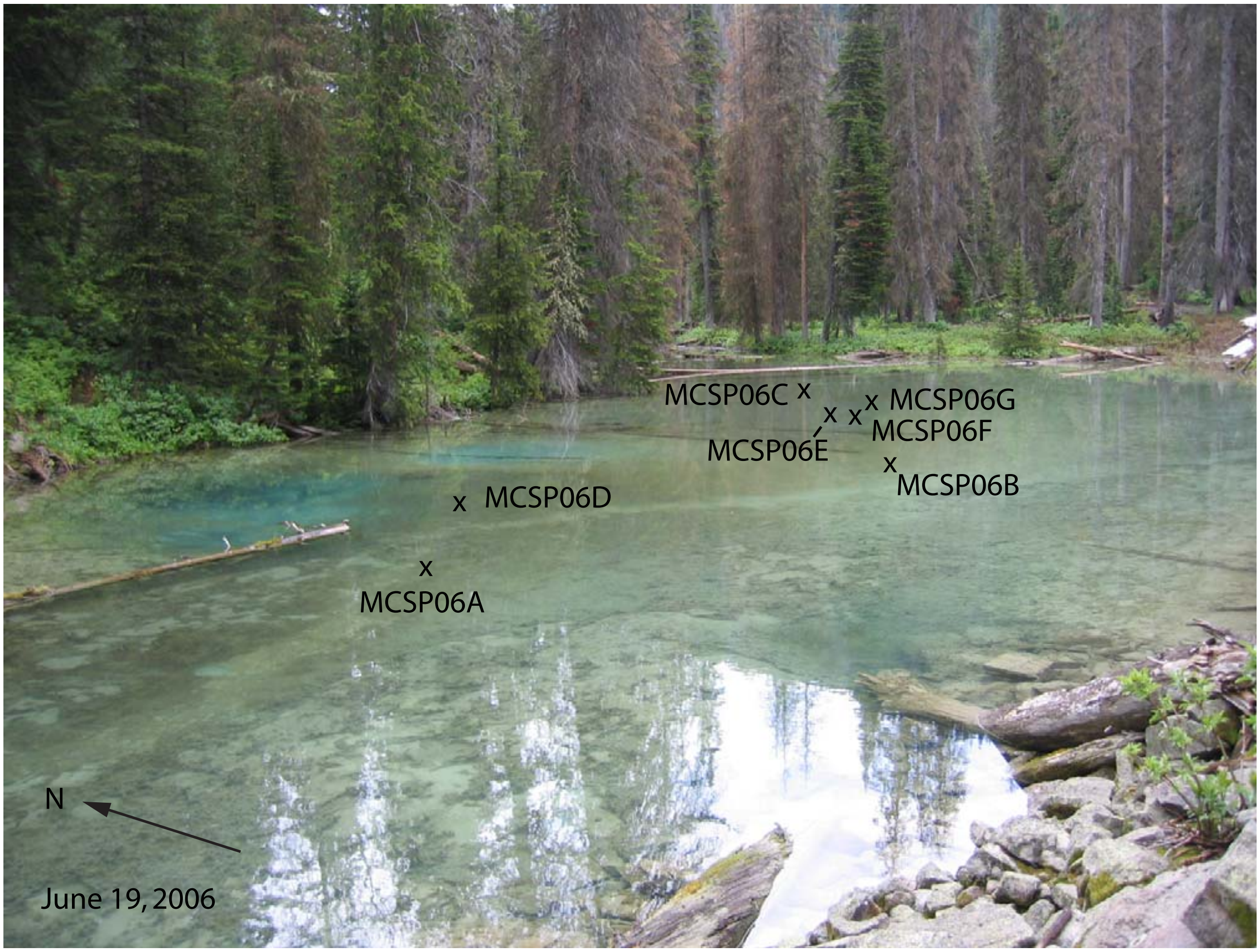

Figure 2. Picture of coring locations during June 19, 2006 (taken by C. Whitlock).

Figure 3. Field pictures of Mammoth Crystal Springs Pond on June 19, 2006 (taken by S. Fritz). (a) southwest talus slope showing inlet and subsurface springs (depressions); (b) collecting core MSCP06E; (c) short core MSCP06D showing mud-water interface, uppermost clay unit and underlying dark silts and sands; (d) woody debris at outlet of east end of pond.

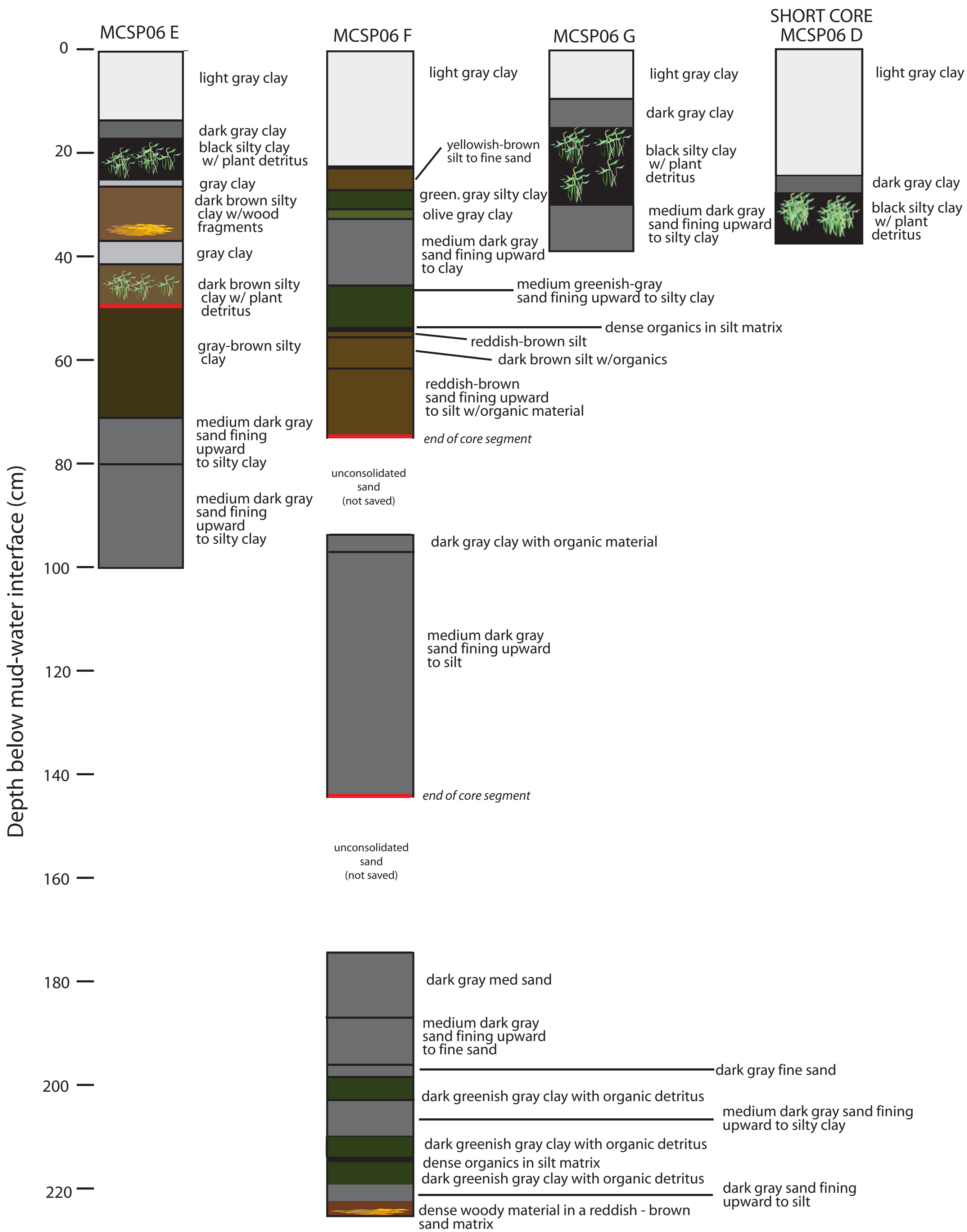

Figure 4. Description of sediment cores from Mammoth Crystal Springs Pond. MCSP06E, MCSP06F, MCSP06G were taken with a Livingstone piston sampler. MCSP06D was taken with a Klein gravity corer. Note that MCSP06F is based on lab descriptions, whereas the other cores were described in the field.

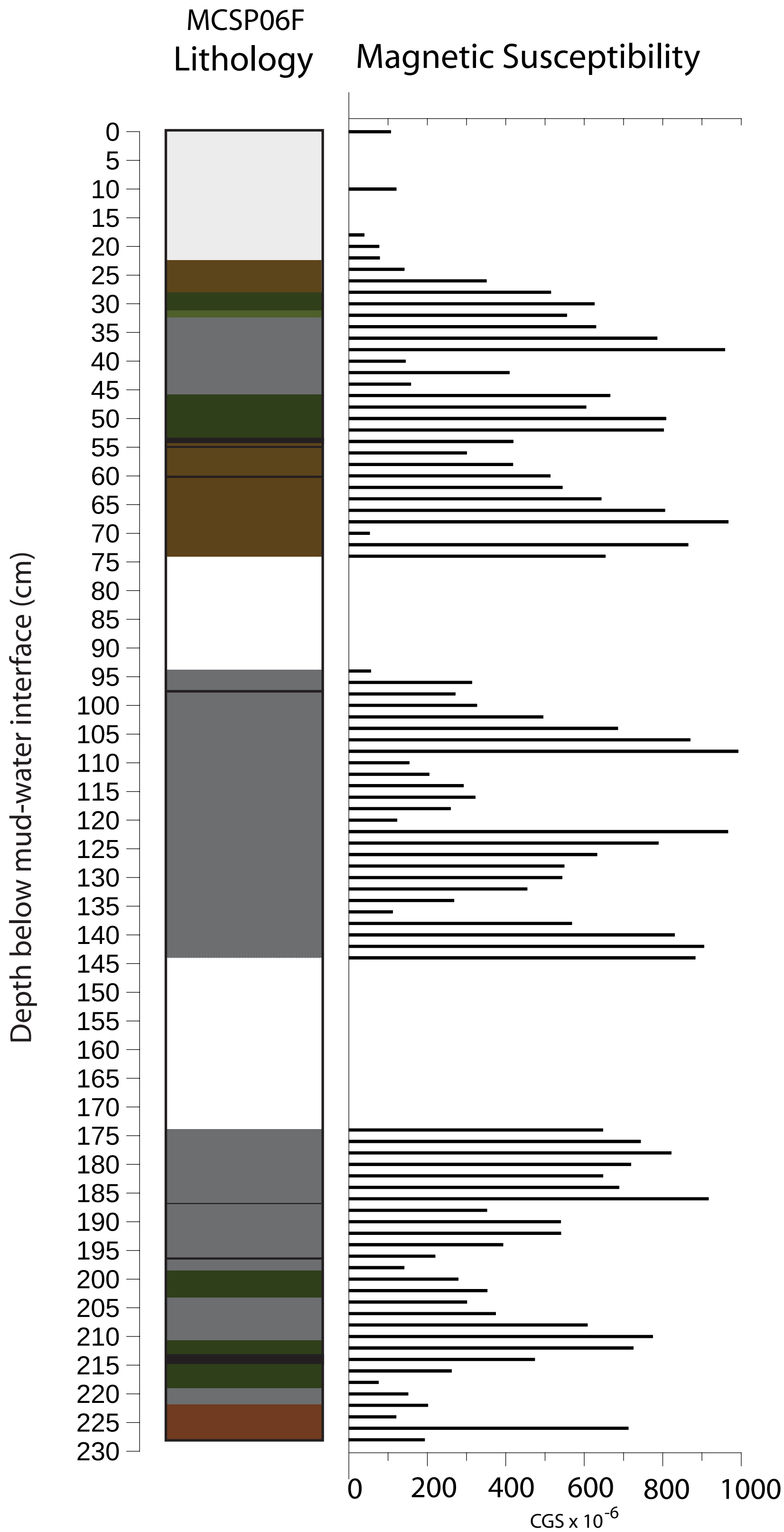

Figure 5. MCSP06F lithology and magnetic susceptibility measurements (see Figure 4 for lithologic descriptions)

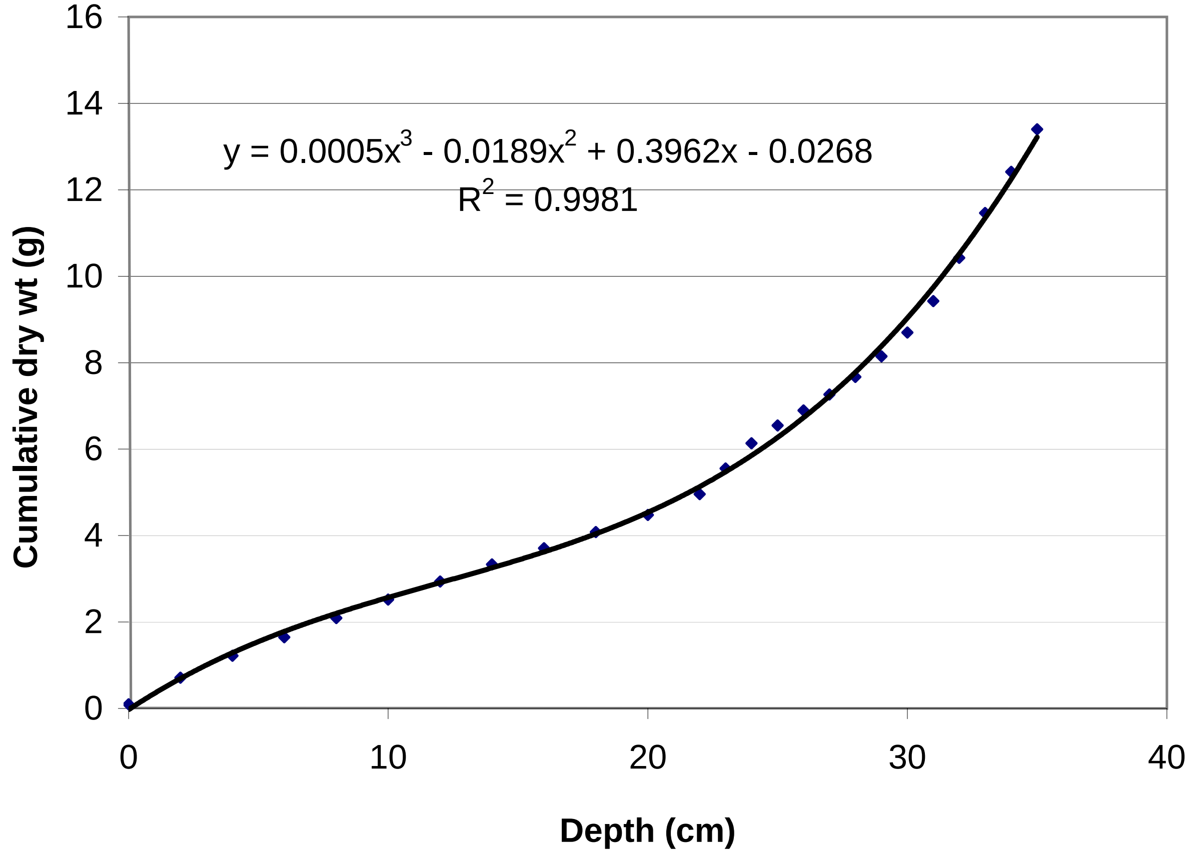

Figure 6. Cumulative dry weight (g) of sediment in core MCSP06D. Note inflection in sediment accumulation rate at 22 cm depth marking the base of the uppermost clay unit.

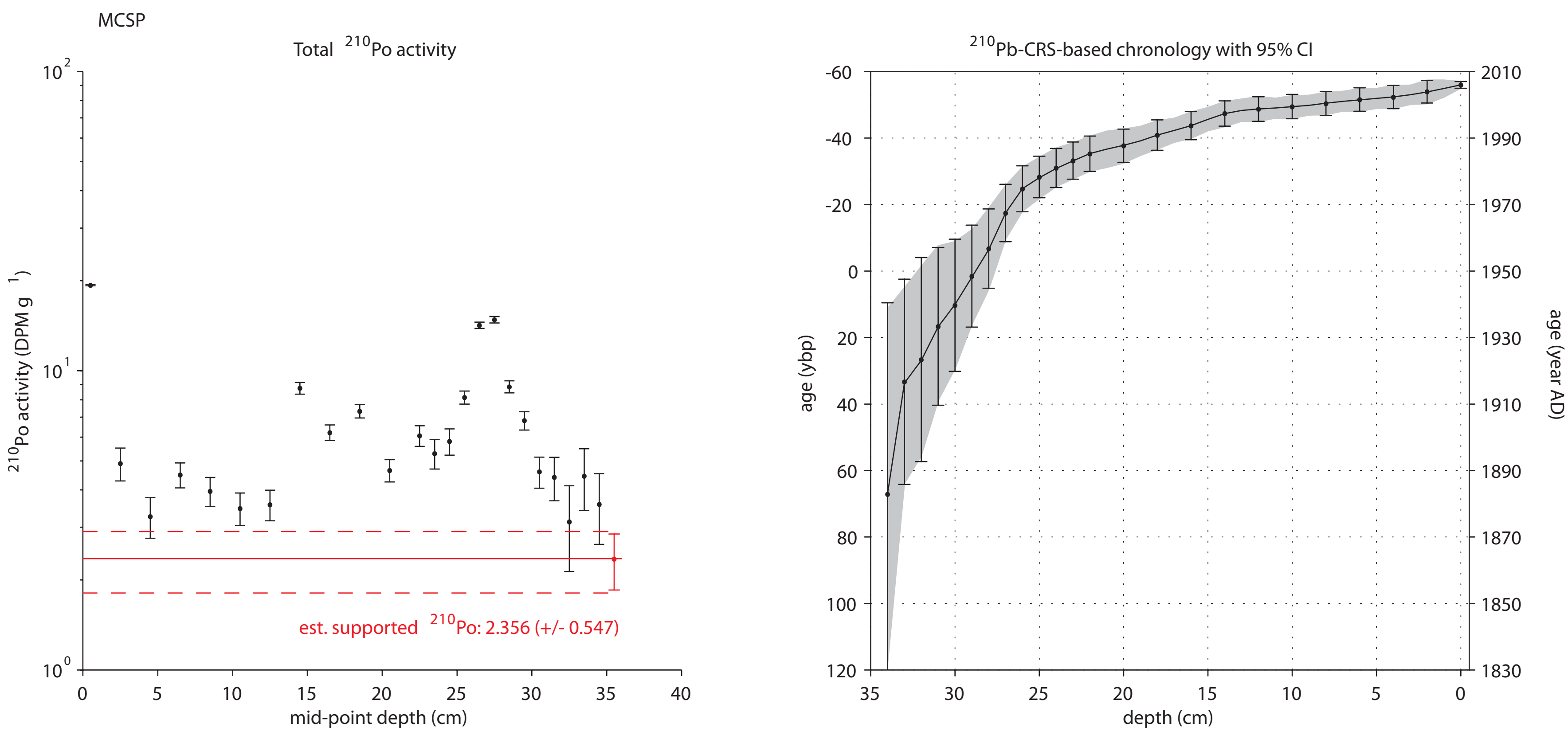

Figure 7. A. Total ^{210}Po activity in the cores, compared to the estimated supported level (2.356 +/- 0.547) at 35.5 cm depth (shown in red). Low values of ^{210}Po activity indicate times of dilution, possibly from rapid sediment accumulation. B. ^{210}Pb Age depth model based on the Constant Rate Supply (CRS) method. Gray bands show error estimates around cubic spline fit based on 1000 random samples of sample ages incorporating their variability (P. Higuera, pers. comm, 2007).

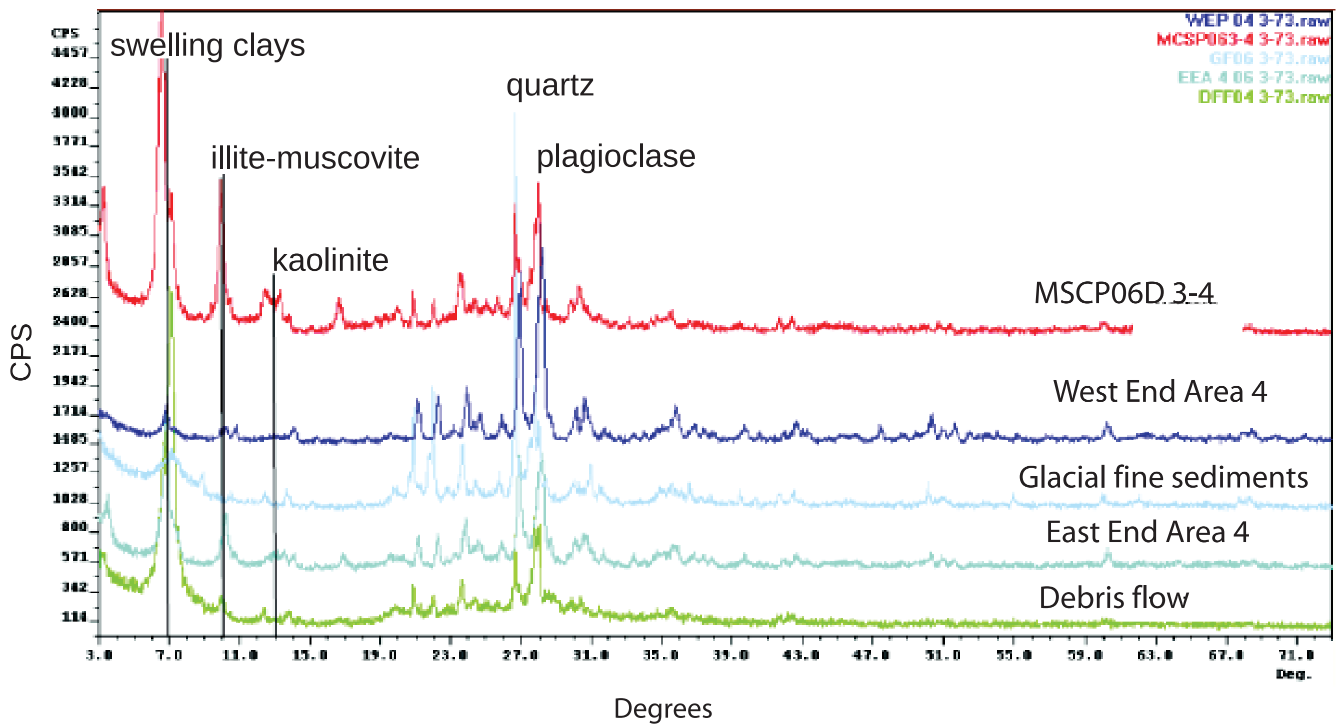

Figure 8. XRD scan results for Mammoth Crystal springs Pond MCSP06D 3-4 cm depth, West End Area 4 (WEP04), Glacial fine-grained sediments (GF06), East End Area 4 (EEA406), and Debris Flow (DFF04). Results are stacked for comparison but scaling is based on the Debris Flow data. Major peaks are labeled according to mineral and clay peak presences. The smaller unlabeled peaks correspond to lesser peaks of already-identified minerals of plagioclase and quartz. Mineral compositions of the samples are similar with the exception of the Glacial fine sediments, which have a greater amount of quartz and lack many of the clay peaks that are present in the MCSP06D 3-4 sample and other samples.

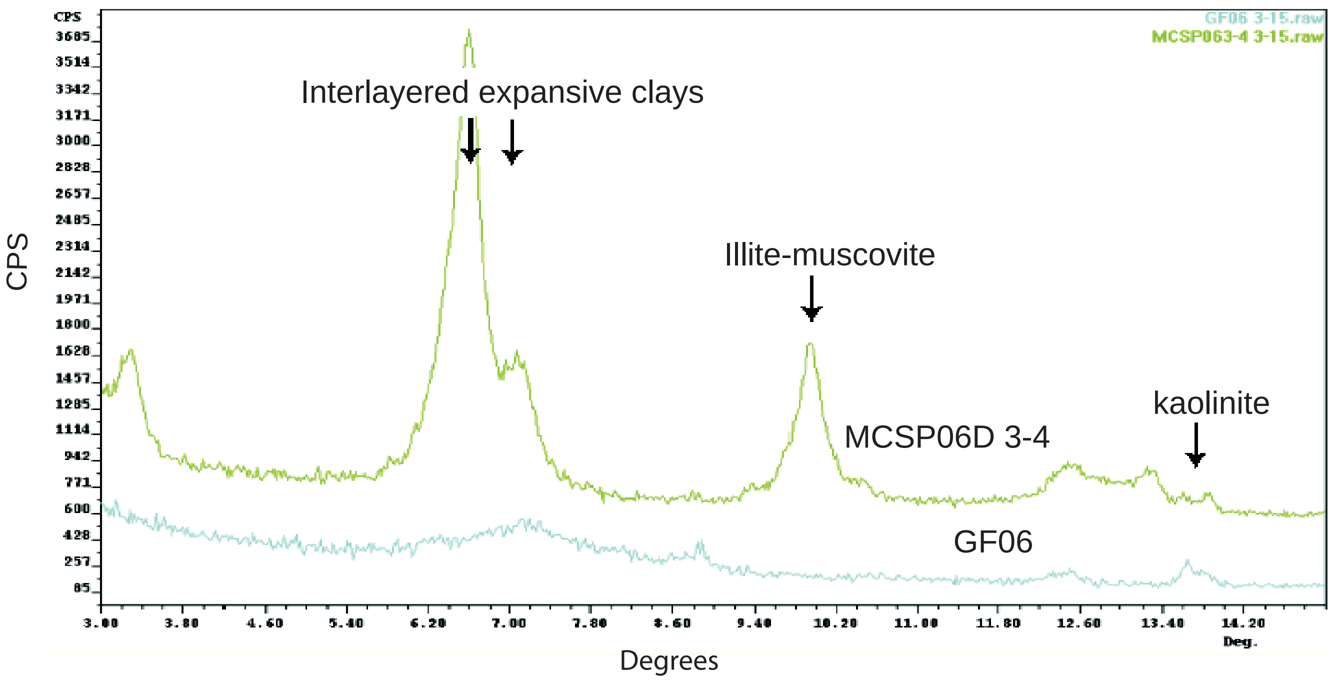

Figure 9. Comparison of clays in Mammoth Crystal Springs Pond (MCSP06D 3-4) and Glacial fine sediments (GF06) at high resoluion from 3-15 degrees, where most clay peaks can be found. GF06 lacks abundance in expansive clays and illite-muscovite minerals relative to MCSP06 3-4.

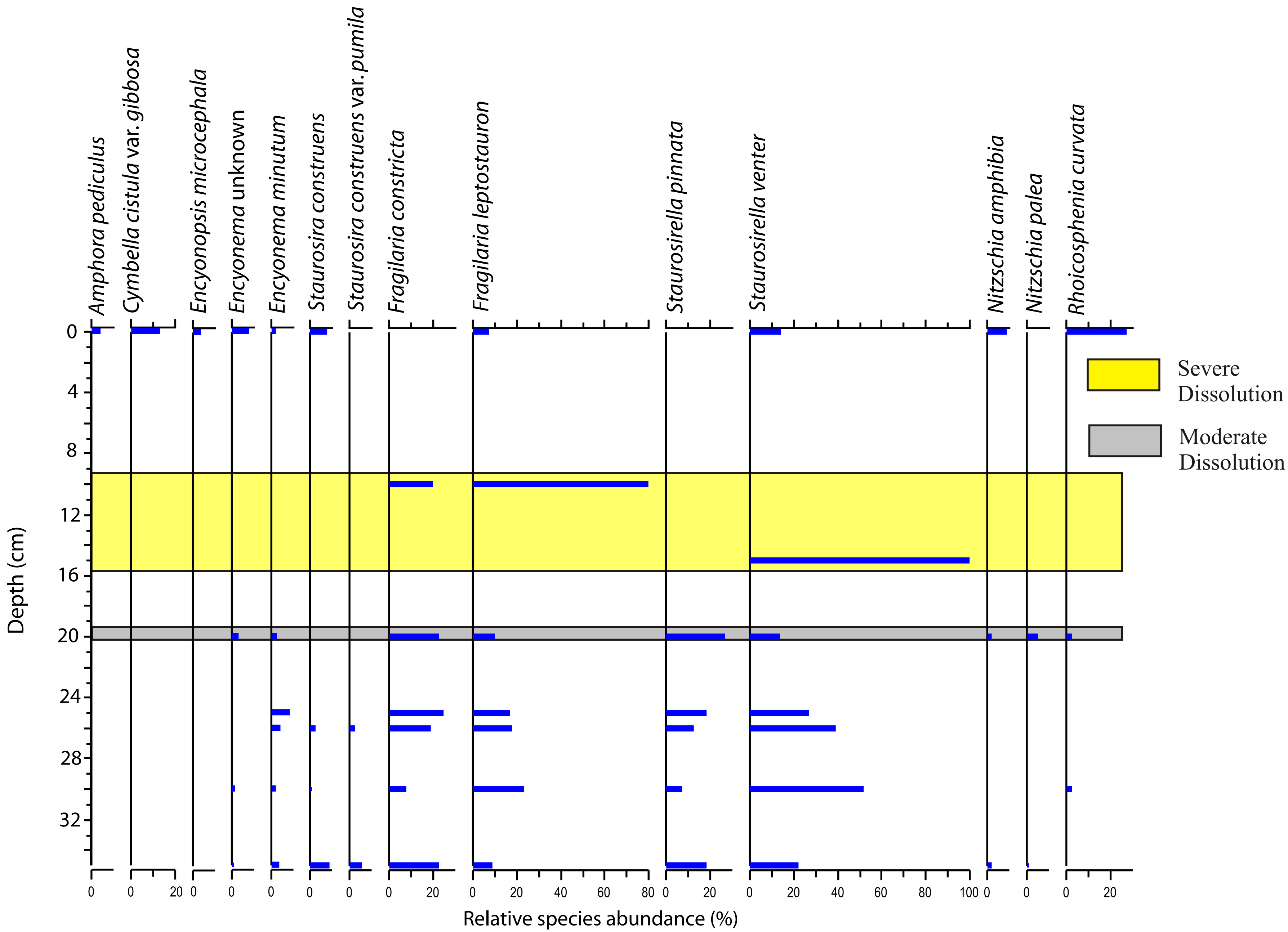

Figure 10. Diatom data from cores MCSP06D and MCSP06F (see text).