Sediment Coring and Analysis in Watson Lake, Arizona

Second Draft

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EXECUTIVE SUMMARY

Watson Lake, in Yavapai County, Arizona, currently suffers from several related water quality impairments: high nitrogen, low dissolved oxygen, and high pH. The lake underwent a major fish kill in 2000. Efforts are underway to assess these impairments through the Total Maximum Daily Load process and to develop strategies to resolve these impairments. This study has been conducted to support these efforts in two ways: first to conduct a bathymetric survey to support water quality modeling efforts and second to collect and analyze sediment cores to provide an assessment of past conditions in the lake.

Sediment cores were collected at two locations in the lake: one near the dam and a second core in the upstream, southwestern basin. The cores were analyzed for magnetic susceptibility, which is a proxy for grain size; the nutrients phosphorus, nitrogen, and carbon; and the stable isotopes of carbon and nitrogen. Analysis of the sediment cores indicated that the bottom of each core dates to the mid-1940s. Measurements of magnetic susceptibility in both cores showed high rates of sedimentation and periodic pulses of mineral sediment from the start of the record until the mid-1960s. Each of these pulses likely resulted from individual storm events. After the mid-1960s, the magnitude of these erosive pulses decreased. Apparently watershed conditions began to favor trapping of sediments upstream from Watson Lake. Presumably much of this trapping occurred in the Watson Wetlands, which has expanded and stabilized in recent decades.

Analytical data revealed a variety of processes in Watson Lake. As with sedimentation, all analytical parameters showed high variability prior to the mid-1960s, associated with frequent episodic delivery of sediment to the lake. Nutrient ratios and isotopic compositions were consistent with loading of nutrients from the watershed. The period from the mid-1960s to the early-1980s showed relatively steady concentrations of sediment nutrients. From the early-1980s to present, concentrations of total organic carbon and total nitrogen began a trend of steady increase. Carbon to nitrogen (C/N) ratios in sediments of this period indicated a mix of terrestrial matter and organic material produced from within the lake.

Starting in the early-1980s, the ratios of nitrogen to phosphorus (N/P) began to rise and the stable isotopes of carbon and nitrogen began a decreasing trend. Organic matter delivered to sediments as relatively consistent ratios of carbon, nitrogen, and phosphorus. An increase in the ratio of nitrogen to phosphorus indicates a loss in phosphorus relative to nitrogen, likely due to the release of phosphate under anoxic conditions in the sediments.

The processes that lead to changes in the carbon isotopic compositions are complex, but can be summarized as follows. In lakes and reservoirs which have low biological productivity, the carbon isotope composition is changed primarily by changes in watershed carbon. In lakes with moderate to high productivity, such as eutrophic lakes, increasing productivity results in more positive values for carbon stable isotopes. In hypereutrophic lakes, in which methane production occurs in the sediment or hypolimnion, carbon stable isotopes can become more negative. The lake is known to undergo anoxic conditions in the hypolimnion. This, combined with the observation of increasing nitrogen and carbon relative to phosphorus, leads to hypereutrophic conditions in the lake as the likely explanation for the negative trend in carbon stable isotopes.

Another factor which can affect carbon stable isotopes is the presence of sewage. Sewage loading to lakes results in a more negative carbon stable isotope value. The observed trends in decreasing carbon isotopes started at about the time sewage outfalls were diverted around the lake, so it appears that sewage itself was not a driving force in the carbon budget of the sediments. However the indirect effects of sewage loading may explain the observed trends in total nutrients and stable isotopes in the later history of the lake.

Nitrogen stable isotope data can provide information on sources of organic matter in sediments. Most biological processes result in more positive nitrogen stable isotope values. As organic matter is decomposed and recycled, its nitrogen stable isotope content increases. Sewage loading results in more positive nitrogen stable isotope content. The only biological process that results in more negative nitrogen stable isotope values is fixation of atmospheric nitrogen. Trends in decreasing nitrogen stable isotopes in both cores indicate the growing dominance of nitrogen fixers, such as cyanobacteria, since the early 1980s.

The conditions in Watson Lake since the mid-1940s can be summarized as follows. From the start of the record to the mid-1960s, the lake underwent periodic loading of sediments from storm events. From the mid-1960s onward the magnitude of these events decreased, presumably due to less erosive conditions in the watershed or better sediment trapping upstream from the lake. After a period of stability in the lake from the mid-1960s to the early-1980s, Watson Lake began a trend of increased primary productivity, with anoxic conditions in the sediments and release of sediment phosphorus into the water column. From the early-1980s onward, the water column became dominated by nitrogen fixers. There is no direct evidence of sewage contamination in the lake. Indirectly, sewage loading could have provided the nutrients necessary to drive primary productivity to the high levels necessary for the current and persistent hypereutrophic conditions observed at present.

To conclude, the sediment record in Watson Lake since the mid-1940s indicates that the lake has made a transition from a system dominated by external loading of sediments and nutrients to a system that is dominated by internal cycling of nutrients driven by summer hypolimnetic anoxia. Abundant phosphorus supplied by sediments favors primary productivity by cyanobacteria. External loading continues to influence the lake, as indicated by C/N ratios that show a mix of terrestrial and aquatic sources.

With regard to management implications, dredging in the southwestern basin of the lake would remove the sediment accumulated since the mid-1960s and expose more mineral sediment in this zone. This would likely remove the burden of sediment nutrient recycling in this part of the lake. The increase in lake volume may buffer the lake better against changes in concentrations of nutrients and dissolved gases. However unless sediments in deeper zones of the lake are removed or inactivated, the same conditions of anoxic release of phosphorus can be expected to continue in these deeper zones.

INTRODUCTION

Watson Lake, in Yavapai County Arizona, currently suffers from several related water quality impairments: high nitrogen, low dissolved oxygen, and high pH. The lake underwent a major fish kill in 2000. Efforts are underway to assess these impairments through the Total Maximum Daily Load process and to develop strategies to resolve these impairments. This study has been conducted to support these efforts in two ways: first to conduct a bathymetric survey to support water quality modeling efforts and second to collect and analyze sediment cores to provide an assessment of past conditions in the lake.

Since its impoundment in 1914, Watson Lake and its watershed have undergone almost continuous change. The lake was created for irrigation and became a recreational amenity for the growing city of Prescott, Arizona, located within the Watson Lake watershed. Reservoirs are dynamic systems and can undergo wide fluctuations in runoff and sediment delivery. Watson Lake has had the additional pressures of lake level fluctuations due to irrigation withdrawals and high levels of nutrient loading associated with urban development. Wastewater effluent, which had entered Watson Lake through its main tributary Granite Creek for decades, was diverted around the lake through a pipeline system in the mid-1980s. The lake continues to receive nutrient loading from sources in the watershed, including storm runoff from the City of Prescott, which has grown rapidly in population since the 1970s.

Watson Lake has been managed more intensively in recent years. Prior to the establishment of a water management plan in the late-1990s which set minimum pool levels, the lake was observed to dry out completely several times in its history. Wetlands at the upstream extent of the lake have been managed and expanded, which may have several positive effects on water quality, including trapping of nutrient-laden sediments and direct uptake of nutrients through growth of wetland plants.

Nonetheless, Watson Lake suffers from the effects of eutrophication. Intense primary productivity creates high demands on dissolved oxygen at night and under low-light conditions. The primary producers also create a high demand for dissolved carbon dioxide during photosynthesis, pushing pH conditions to high levels. As a result, summertime concentrations of dissolved oxygen and carbon dioxide make dramatic swings over the 24-hour diel cycle and create physical stress on aquatic organisms.

An important objective in conducting the TMDL on Watson Lake is to understand driving forces behind the current eutrophic conditions. The lake is known to have high nitrogen concentrations presently, but it is unclear how long the lake has supported this level of productivity. It is also known that during summer stratification, the lake undergoes intense anoxia in the hypolimnion, however the importance of nutrient transformations that occur under these conditions, relative to nutrients entering the lake through runoff, is not well understood.

Analysis of sediment cores has the potential to provide relevant information in several areas. Patterns of sediment delivery to the lake can provide information on changes in sedimentation over recent decades. Analysis of nutrient concentrations and isotopic ratios can provide information on the delivery of nutrients to the lake, the relative amounts of organic matter delivered from the watershed versus produced within the lake, and the magnitude of past primary productivity.

METHODS

Bathymetry

A bathymetric survey of Watson Lake was conducted on May 14 and 15, 2009 using a sonar depth finder attached to a consumer-grade GPS unit. Prior to the survey transects were designed to create a grid approximately 70 x 70 meters in the upstream (southwest) basin and approximately 50 x 50 meters in the downstream (northeast) basin. Using this grid, navigation waypoints were established where each transect met the shoreline. The survey was conducted using a motor-boat by setting a course using the navigation waypoints and surveying at a steady speed. Bathymetric data were collected using a Humminbird Matrix depth finder for water depth. Position was provided by a Garmin GPS 76 with 3D differential GPS capability. The GPS unit was connected to the sonar device and communicated through NMEA protocols so that a single file was created with position and depth information. Precision of the GPS unit in 3D Differential mode was within one meter.

The sonar depth finder recorded depth in meters. To correct for environmental conditions, boat movement, and the position of the sonar transducer in the water, a series of observations was made whereby the boat passed at normal cruising speed alongside buoys which marked locations of known depth. Depth at the buoys was verified using a measuring tape. A regression equation was developed to correlate the true depth to the depth recorded by the sonar depth finder (Figure 1). Depth observations were then corrected to depth below full pool using visual observations of the staff gauge at the dam and records of lake level for the dates of the survey.

At the time of the survey the lake level was high. The lake level on the dates of the survey was 1.61 feet below full pool. So the survey reflected almost full lake conditions. To provide additional information for the map, geo-referenced aerial imagery was acquired from the USGS Seamless Map Server. Shorelines were digitized and the lake level was determined for the date of the image. The images used were taken on July 5, 2002 (Lake level = 14.61 below full pool) and June 21, 2007 (Lake level = 10.59 feet below full pool).

The position and corrected depth data were assembled into a spreadsheet and imported as a point shapefile into ESRI ArcGIS. A digital elevation model was made by testing two methods of interpolation: kriging and nearest neighbor. Of the two, kriging best represented reasonable bathymetric conditions. The bathymetric data included points that were near to each other (~ 1 meter along transects) as well as data separated by relatively great distances (~ 50 meters between transects). Kriging was found to have minimal distortions due to the imbalanced data spacing.

Sediment Coring

Coring locations were selected in consultation with ADEQ and are shown in Figure 2. Sites were selected to represent lacustrine conditions (Site A) and more riverine conditions (Site B). Sediment cores were collected from the deck of a floating platform assembled on site. Two coring devices were used. To collect cores from the sediment-water interface to about 50 cm below the interface, a 5-cm diameter pistonless corer was used, attached to a solid rod. This device has a check valve in the coring head, rather than a piston, to suspend the core in the coring tube by vacuum. This device was used to collect Surface Cores A and B. Cores collected with this device were sampled in the field at 1-cm intervals to a depth of 10 cm below the top of the core to collect the high moisture content sediment near the top of the core. Samples were stored in plastic storage bags. The cores were then sealed for transport to the laboratory.

Longer cores were collected using a Wright-Livingstone square-rod piston corer (Wright et al., 1984). This device was also attached to a solid rod and collects cores in one-meter segments. These segments were extruded intact in the field, wrapped in plastic wrap and aluminum foil, and stored in split-PVC pipe segments. Cores were identified by number (e.g., Core 1) and by the drive number, with Drive 1 being the first collected, and so on. The first drive of each core started at 20 cm below the sediment-water interface to avoid the unconsolidated sediment in the upper centimeters.

Initial Sample Preparation

Once sediment cores were recovered from the field, they were stored in a locked walk-in cooler at 4^{o} C until processing. Surface cores were sampled in the lab at 2-cm intervals, stored in plastic storage bags, and returned to the cooler. Intact Livingston cores were split and observations were made on the appearance of the cores. These lithologic descriptions are provided in Appendix A. For each core drive, the datum was the top of the drive and measurements were made in cm from the top of the drive. Data are presented in this report as the cumulative distance from the sediment-water interface. Because the Livingstone cores were started below the sediment-water interface, a correction was applied based on matching up plutonium concentrations in the surface core and the Livingstone core. This process is described later in Chronometry.

After the lithologic description was performed, the split core halves were analyzed for magnetic susceptibility (MS) at 5-mm intervals using a Bartington Magnetic Susceptibility analyzer with units reported in the cgs system. The split cores were then returned to cold storage to await sampling. The surface cores did not undergo this preliminary analysis.

Core Sampling

Samples were collected from the cores for analysis. The surface cores had already been sampled into 1-cm intervals for the first 10 cm and 2-cm intervals below. For both surface cores, samples from 0 to 20 cm, 20 to 24 cm, and 44 to 48 cm were selected for analysis, for a total of 42 samples. The Livingstone cores remained intact and were sampled at intervals reflecting lithology. For both Livingstone cores combined, a total of 54 intervals were sampled, ranging from 2 to 10 cm in length and averaging 6.6 cm. Intervals were continuous. For example, Core 2 Drive 1 was sampled from 0.0 to 5.0 cm, then from 5.0 to 8.0, then from 8.0 to 18.0, and so on. As a result the entirety of the core drives from Site A and Site B was sampled.

Wet samples were collected, weighed, and placed in a laminar-flow chamber to air-dry. After at least 72 hours, the samples were weighed, crushed to a powder, reweighed, and returned to the chamber to release internal moisture (typically about 0.2 percent). After final weighing, samples were divided into aliquots for analyses.

Analytical Methods

Samples were analyzed for plutonium for dating, total nutrients (carbon, nitrogen, and phosphorus), nitrate nitrogen, and the stable isotopes of carbon and nitrogen. All 96 samples collected were analyzed, however for some analytes, two to four adjacent samples were composited to reduce the total number of analyses. The decision of which samples to composite was based on targets for total numbers of samples to be analyzed for each parameter and core lithology. For total carbon, total nitrogen, and the carbon and nitrogen stable isotopes, all 96 samples were analyzed; for plutonium 47 samples were analyzed; and for total phosphorus and nitrate 40 samples were analyzed. Appendix B provides a listing of the samples composited for each analyte.

Total phosphorus and nitrate nitrogen were analyzed by the University of Arizona, Environmental Research Laboratory. Total carbon and total nitrogen were obtained along with carbon and nitrogen stable isotopes and were analyzed by the Colorado Plateau Stable Isotope Laboratory at Northern Arizona University. Plutonium was analyzed at Northern Arizona University in the Michael Ketterer laboratory.

RESULTS

Bathymetry

Bathymetric data were collected for Watson Lake in May 2009 and by digitizing shorelines from aerial imagery collected in 2002 and 2007. These data were assembled into a point file and a digital elevation model (DEM) was developed using ESRI ArcGIS 9.3 Spatial Analyst software. Interpolation was conducted using kriging techniques. The raw DEM file resulting from the interpolation extended beyond the full-pool shoreline boundary, so a polygon mask in the shape of the shoreline was used to clip the DEM to the lake boundary. The resulting bathymetric map is shown in Figure 2. To support water quality modeling efforts, the DEM was analyzed to develop profiles of surface area and volume as a function of depth below full pool. The ESRI ArcGIS 9.3 tool Area and Volume Calculations was applied at 0.5-meter depth intervals to produce the table and plots shown in Figure 3. These calculations indicate that at full pool the lake has an average depth of about 4.8 m.

Chronometry

Chronometry for the cores can be estimated from known date markers and by radioisotopic markers. Radioisotope dating can provide date markers for the onset of above-ground in about 1953 and the enactment of the nuclear test-ban treaty in 1964, which marks the peak of above-ground atomic testing and the highest rate of global radioactive fallout. The radioisotope cesium-137 (^{137}Cs) has been the most commonly used fallout indicator. However the relatively short half life (about 30 years) of ^{137}Cs means that the supply of bomb cesium is diminishing. In addition the analysis is time consuming and requires relatively large sample sizes. An attractive alternative is the analysis of two plutonium isotopes, ^{239}Pu

and ^{240}Pu. Recent advances in instrumental techniques enable the analysis of these isotopes using mass spectrometry.

Both cores were analyzed for $^{239+240}Pu$ and the results are plotted in Figure 4, along with magnetic susceptibility (MS). MS can be used as a proxy for erosive events and can assist in the interpretation of the Pu data. Assigning dates to locations in the Pu curves requires interpretation of the data, which is described below in the Discussion section.

Data plots for Pu and the analytical data described below show the analytical parameter plotted versus depth for the surface core and the Livingstone core on the same chart. During field sampling, the coring device was set to start collecting the Livingstone cores at both sites 20 cm below the sediment-water interface. In terms of absolute depth below sediment, the Livingstone cores should then be plotted starting at 20 cm on the Depth axis. This offset corrects relative depth in the Livingstone core to absolute depth. In this case the offset would be 20 cm. Due to variability in field conditions though, the core drive does not necessarily start precisely at this depth. To determine the offset for each site, trial values were used until the Pu curves for the surface core and Livingstone core matched (Figure 4). The offsets were determined to be 20 cm for Site A and 19 cm for Site B. As will be seen in the analytical data below, these offset values are not ideal for every parameter, but do provide reasonable matches for most parameters.

Analytical Data

Results for the analytical parameters are plotted for total nutrient data in Figure 5 and isotopic data in Figure 6 versus depth in the cores. Included as a reference in the plots of Figures 4 through 6 are the plots of magnetic susceptibility. MS is a measure of the mineral magnetic content of sediment. In most reservoirs, MS is a reliable proxy for particle size. Depending on watershed geology, more massive particles tend to represent parent geological material and have higher ferro-magnetic content. Finer particles tend to be associated with clays and organic matter that have lower magnetic content. Note that the scales for MS are different for Cores A and B; MS values in Core B were much higher and indicate a higher erosive load in the upstream basin of Watson Lake. MS was analyzed only on the intact Livingstone cores. Procedures to analyze for MS on crushed samples are considerably more involved, so it was not possible to analyze the surface cores for MS, which were not kept intact. The MS data show systematic pulses that track closely with lithologic features and appear to indicate storm event deposition. Peak MS values were higher in Core B than in Core A which is consistent with sedimentation of coarser particles toward the riverine end of the lake.

A statistical summary of the analytical data is provided in Table 1. Core B had substantially higher MS (Average = 153 cgs units) than Core A (Average = 55 cgs units) and had a maximum value of 675 cgs units compared with a maximum of 184 in Core A, which is consistent with higher mineral loading from the watershed. Among all of the nutrient parameters, Core A had higher mean and maximum concentrations, particularly with respect to total nitrogen (TN).

Two nitrogen forms were measured, TN and nitrate nitrogen expressed as the equivalent weight of nitrogen (NO_3-N). Total nitrogen consists of organic, ammonia, nitrate, and nitrite. The nitrate component was consistently three orders of magnitude lower than total nitrogen. In Core A, for example, nitrate averaged 2.9 ppm, while total nitrogen averaged about 3,300 ppm. Both isotopic records were more enriched in Core A than in Core B, although only by less than 2 ‰ compared with observed ranges of 4 to 7 ‰. With regard to temporal variability fluctuations in the nutrient and isotopic parameters appeared to be associated with fluctuations in the MS record, indicating influences of storm events. All parameters showed systematic change in the top 20 cm of the core.

DISCUSSION

Chronometry and the Depositional Environment

Interpretation of the analytical data requires careful attention to the timing of the delivery of the sediments. Analysis of chronometry and sediment delivery can provide information on changes in watershed characteristics as well as provide the ability to assign estimates of date to positions in the core and correlate changes in sediment chemistry to past events in the lake and watershed.

Reservoir sediment records can be dated using radioisotopes and events of known date that can be recognized in the core. One objective in reservoir coring is to be able to collect a core that includes the pre-impoundment native geological material. This can provide a reliable end date for the core. In some cases deposition of sediment from high-intensity storm events can be recognized in the core. The chronometry for the Watson Lake cores relied almost exclusively on the radioisotope record. The total length of the cores, about 220 cm in Core A and 165 cm in Core B, were both less than the expected amount of sediment for a reservoir impounded in 1914. The radioisotope record confirmed this, as Pu was detected within 30 or 40 cm of the bottom of the core.

A clear, although complex, Pu signal was found in both cores. In natural lakes, oceans, and polar snow records, the record of fallout isotopes with depth resembles the concentration of atmospheric deposition over time: zero concentration until the early-1950s with an exponential buildup to 1964, followed by a sharp decline after 1964. Depending on how watersheds release these radioisotopes the shape of the post-1964 may be more or less attenuated. The classical model for natural lakes with relatively undisturbed watershed, however, is a concentration curve with a single distinct peak. Shapes other than this are commonly interpreted as distortion of the input signal through mechanical reworking of sediments, for example through turbidity plumes, or bioturbation by benthic organisms.

Both Pu curves (Figure 4) show clear ascending and descending limbs but instead of distinct peaks, the curves show plateaus of relatively high Pu activity. These plateaus occupy a large portion of the sediment record. Instead of a single distinct peak in Pu activity, Core A shows high Pu activity over an 80-cm span in the core, with a 30-cm span in Core B. If the sediments had been mechanically mixed, the lithologic records of these intervals should show indistinct features, or more likely, an absence of features altogether. However the MS records during both of these intervals shows highly systematic changes in MS, with Core B having consistently higher-magnitude peaks in MS than Core A. Peaks and troughs in MS occurring over tens of observations are clearly observed. The lithologic record shows distinct, undisturbed strata associated with these changes in MS. Figure 7 reproduces one of the lithologic logs during the period of high Pu in Core B. Preservation of the complex record of sediment deposition is a clear indication that although Watson Lake had a dynamic depositional environment, the bottom sediments at Sites A and B have not been reworked over time.

The protracted Pu curves in Cores A and B indicate a variable sedimentation rate. The date of 1953 was assigned to positions 174 cm in Core A and 140 cm in Core B, and the date of 1964 to positions of 77 cm in Core A and 77 cm in Core B. This results in post-1964 sedimentation rates of 1.6 cm/year at both Sites and B. The pre-1964 sedimentation rates however were 8.8 and 5.4 cm/year at Sites A and B, respectively. This represents a dramatic decrease in sediment delivery in recent decades. Assuming these date markers are correct, the reduction in sediment delivery must have been due to some combination of reduction in the intensity of erosive conditions in the watershed and improved sediment trapping in the watershed.

Historical records of sediment delivery to Watson Lake were not collected, and inflow data do not span the time interval captured by Cores A and B. The base of the cores corresponds to about the year 1947 in both cores. Flow records were maintained in Granite Creek from 1932 to 1947 and did not resume until 1994. The precipitation record is available for the entire period, however unless hydrologic models are applied, these data do not convey adequate information about how water or sediment was delivered to the lake. Figure 8 plots the precipitation and available flow data for the Watson Lake watershed.

Sedimentation rates based on the Pu record indicate that higher erosion occurred prior to 1964 than after 1964. For precipitation to be an indicator of past erosive conditions, there should be an indication of higher amounts of precipitation prior to 1964. Figure 8 shows quarterly sum precipitation, but it is difficult to interpret this record directly. Figure 9, shows a ranking of precipitation totals. This figure includes only the top 25 quarterly periods. Of these, six dates are before 1964 and the remaining 18 are after 1964. The period of record spans 66 years, 19 before 1964 and 47 after 1964. An even distribution of precipitation events would predict that 28 percent of the top 25 precipitation quarters should occur before 1964, which works out to 7.2 quarters. Six quarters prior to 1964 rank in the top 25, which indicates that the records are balanced; roughly the number of pre-1964 events show up in the top 25 as would be expected. Therefore, in terms strictly of storminess, the years prior to 1964 did not deliver any more precipitation than the years following. In fact, the top 5 quarters for precipitation all occurred after 1964.

The depositional environment in Watson Lake has been influenced by factors other than storm intensity. Antecedent conditions, the sequencing of precipitation amounts over a series of days, and other factors determine a storm's contribution to the sediment record. As will be discussed later, a major storm event in 2005 had a significant effect on Watson Lake and mobilized fallout Pu that had remained in the watershed since the atomic testing era. This can be seen as Pu peaks toward the top of Cores A and B (Figure 4). This event is prominent in the flow record from 1994 to 2011 (Figure 8), but this time period ranks only 23nd in terms of precipitation. Two important factors preceded the 2005 storm event. One was the 2002 Indian fire. Although it occurred three years previously, no major storm events occurred until the 2005 storm. In fact, the year prior to the 2005 storm was dry enough that lake level had fallen to 12 feet below full pool in Watson Lake. It appears that the Indian fire brought about conditions in the watershed that enabled Pu to be mobilized by the 2005 storm event. As will be discussed later, the 2005 event also had a major impact on sediment chemistry.

To summarize the analysis of sedimentation in Watson Lake, sedimentation rates prior to 1964 were significantly higher than those after 1964. Statistical analysis of precipitation (Figure 9) shows there is no evidence to suggest that climatic conditions have changed to reduce sediment loading since 1964 and in fact the five rainiest quarters in the period occurred after 1964. The example of the 2005 storm provides an indication that erosive conditions cannot necessarily be well predicted by precipitation alone. The lithologic and MS records from Cores A and B both clearly indicate that sediments have not been disturbed in long segments of the core which bear the unmistakable imprint of the time period of 1953 to 1964. Two conclusions that may be drawn are that the date markers for 1953 and 1964 (Figure 4) are correct, and consequently sediment delivery to Watson Lake has decreased significantly in the decades following 1964.

The data in Figures 4 through 6 are plotted versus depth in the core. When these data are re-plotted using an age model based on the date markers of Figure 4, the data below the 1964 positions become greatly compressed. This can be seen in Figures 10 and 11, which plot data versus year. The MS records, for example indicate highly dynamic conditions in the years prior to 1964, with rapid successions of high-magnitude erosion events. After the mid-1960s both the magnitude and frequency of major erosive events decrease. Interpretations of nutrient and isotopic data will be made within the context of this changing depositional environment.

Nutrient Concentrations and Ratios

Changes in the patterns of erosive deposition to Watson Lake also brought about changes to nutrient loading to the lake, however the sediment record shows that other factors affected the nutrient budget of Watson Lake as well. The sediment record prior to 1964 shows building and variable concentrations of the macro-nutrients phosphorus, nitrogen, and carbon (Figures 10 and 11). After 1964 the three macro-nutrients showed variability associated with erosion events, but did not exhibit any upward or downward trend.

It should be noted that in Core B, there appears to be a mis-match between the top of the Livingstone Core and the bottom of the Surface Core (Figure 11). For example the rising trend in total nitrogen observed to begin around 1991 in the Livingstone Core does not appear in the Surface Core until about 2000. However both cores match well in the 1980s. This discrepancy is likely due to compression of the top of the surface core. The age model for Surface Core B should be re-evaluated, particularly in regard to interpreting the effects of the 2005 storm event.

From about 2000 onward, both cores show trends of increasing concentration in total organic carbon and total nitrogen, with peaks occurring at about the onset of the 2005 storm. The 2005 storm event seemed to change the trajectory of lake processes. Total organic carbon and total nitrogen made abrupt decreases, presumably due to mineral dilution, with subsequent variability in concentration to the present. Changes in nutrient concentrations prior to the onset of the 2005 storm can be interpreted in terms of nutrient ratios and isotopic compositions.

Ratios of the macro-nutrients C, N, and P are useful indicators of past environmental conditions. The well-known Redfield ratios (Redfield 1958) were originally based on the relative elemental concentrations of macro-nutrients and less abundant elements from samples of marine phytoplankton. Redfield's work forms the basis for theories of nutrient limitation under the assumption that the dietary requirements of plants are equal to their nutrient compositions. Redfield's presented C:N:P ratios of 106:16:1 on an atomic basis, which corresponds to mass ratios of about 40:7:1 (Schindler et al., 2008), or an N:P ratio of about 5.7 by mass. Although Redfield's original work was limited to analysis of marine phytoplankton, this work has been extended to other form of organic matter (e.g., Meyers and Lallier-Vergès 1999). C:N:P ratios are not necessarily good indicators of sewage loading, however, since the organic matter associated with sewage has been observed to have nutrient ratios comparable to the Redfield ratio (e.g., Bickford 1996).

Considering first the ratios of carbon and nitrogen, the mid-1940s to the mid-1960s is a period that starts with the highest C/N ratios (Figures 10 and 11) which range from greater than 14 at the beginning of the record to about 8 by the mid-1960s in Core A and 10 in Core B. Vascular land plants, which build cellulose tend to have high C/N ratios. C3 metabolism plants commonly have C/N in excess of 20 and C4 metabolism plants have C/N in excess of 40, while phytoplankton tend to have much lower C/N ratios on the order of 4 to 10 (Meyers and Lallier-Vergès 1999). The use of C/N ratios to infer the origin of organic matter has become a common tool in aquatic sediment analysis (e.g., Torres et al., 2012; Antoniades et al., 2011; Tepper and Hyatt 2011; Filstrup et al., 2010; Das et al., 2008; and Routh et al., 2009 among many others).

The C/N ratios in Watson Lake indicate that the highest proportion of terrestrial organic matter occurred before the 1960s and following that, organic matter was composed of a combination of terrestrial and aquatic organic matter predominated by aquatic biomass. It is notable that the C/N ratios at the Core A site began a gradual increase from about 8 in 1980 to 11 in 2011. The cause for the increase is unclear, but the nitrogen isotopic record described below does not indicate that this is due to increased external loading.

Analyses of sediment nutrient ratios that involve phosphorus are complicated by the fact that P becomes mobile under anoxic conditions. In fact comparisons of C/N and C/P ratios in sediment records have been used to infer and even quantify the magnitude of anoxia in marine basins (Emeis et al., 2000). They argue that under conditions of oxygen availability and assuming that the sediment record is composed of organic matter of constant origin, the ratios of C/N and C/P should show similar patterns of change. Under anoxic conditions P mobilization may be recorded as a higher C/P ratio compared with the record of C/P, since the mere presence of anoxia should have no effect on organic C/N ratios. Expressed another way, ratios of N/P should show more positive values under conditions of anoxia. Quan and Flakowski (2009) provide a thorough theoretical basis for redox effects on N/P ratios in aquatic sediments.

Sediment ratios of N/P may also be affected by runoff and water column processes. For example Lu et al. (2010) theorized that observed changes in N/P in Lake Erie sediments may have been due to high nitrogen loading from runoff being assimilated into plankton biomass, and subsequently organic sediment, in one part of the lake's history, followed by low N/P ratios reflecting subsequent nitrogen limitation in the water column later in the lake's history.

The sediment record of both cores in Watson Lake (Figures 10 and 11) show patterns of somewhat variable N/P prior to 1964, consistent with variations in external loading, followed by about three decades of steady N/P. From the mid-1980s in Core A and mid-1990s in Core B, N/P starts a significant increasing trend that continues to present. The total nutrient data show that this is due to steady or decreasing TP and increasing TN, with corresponding increases in TC. The simplest explanation for these changes is that phosphorus has been held more or less constant in the sediment record by loss through mobilization during anoxia, while carbon and nitrogen have accumulated at rates proportional to production in the water column combined with introduction from external sources. If this is the case, biological productivity and nutrient loading have been reasonably steady from the mid-1940s to the mid-1990s. From the mid-1990s to present, some combination of nutrient loading and biological productivity have been increasing, with hypolimnetic anoxia providing positive feedback for productivity in the form of a mobilized phosphate source.

Carbon Isotopic Processes

The stable isotopic ratios of carbon and nitrogen provide an additional dimension to understand the sediment record. These isotopes can be useful indicators of past environmental conditions because biochemical processes typically uptake the more abundant lighter stable isotope preferentially (for example the uptake of ^{12}C preferred over ^{13}C) thereby altering the pool of remaining material. To some degree different biochemical processes show varying preference for the lighter isotope. This preference is the driving force for isotopic signatures which can be traced in ecosystems.

The two primary uses for carbon stable isotopes in aquatic sediment studies are to determine the source of carbon and past intensity of productivity. As already discussed, various plant metabolisms have unique isotopic signatures. Terrestrial plants vary in $\delta^{13}C$, with C3 metabolism plants (generally woody plants) typically having $\delta^{13}C$ from about -22 to -33 ‰ and C4 metabolism plants (generally grasses and grains) having $\delta^{13}C$ from about -8 to -22 ‰. Freshwater algae range in $\delta^{13}C$ from about -12 to -30 ‰ and vascular macrophytes range from about -20 to -30 ‰ (Meyers and Teranes 2000). In a study of Finnish lakes, Vuorio et al. (2006) observed the $\delta^{13}C$ range in cyanobacteria to vary between -6 and -32 ‰ with the particular taxon *Gloeotrichia*, ranging from -6 and -14 ‰. These broad ranges reflect the range in isotopic composition of the source pool of dissolved inorganic carbon (DIC) as well as the metabolic preferences of the organism itself.

Much of the variability in $\delta^{13}C$ observed in photosynthetic organisms is due to variation in the isotopic composition of the source DIC pool. There are three models for how $\delta^{13}C$ in organic matter changes in response to trophic conditions in lakes. Under conditions of low or moderate productivity (first model), the rate of DIC replenishment through atmospheric exchange may enable the isotopic composition of the DIC to remain more or less unchanged and the organic matter produced through photosynthesis may have a relatively steady $\delta^{13}C$ composition. However under conditions of more intense photosynthesis (second model), the DIC pool may become sufficiently depleted in ^{12}C that the primary producers have no choice but to uptake greater quantities of ^{13}C, resulting in more positive $\delta^{13}C$ ratios. This has been observed in many eutrophic lakes (e.g., Schelske and Hodell 1995 and Brenner et al., 1999). Under conditions of primary productivity sufficiently high to create high pH conditions, free CO_2 may be removed completely, compelling photosynthesizing organisms to use bicarbonate ion as a DIC source. Bicarbonate ion can be as much as 8 ‰ more positive than free CO_2 (Brenner et al., 1999) creating organic matter with more positive $\delta^{13}C$.

The model of increasing $\delta^{13}C$ with increasing primary productivity is valid when primary productivity controls the carbon cycle. In lakes with organic sediments and intensely anoxic hypolimnia, the activity of heterotrophs can exert a force on the carbon cycle and leave a strong isotopic imprint (third model). Under anoxic conditions, methanogenisis produces methane highly depleted in ^{13}C (-60 to -110 ‰, Grossman et al. 1989). Methanotrophs using this methane as a carbon source, both produce organic matter depleted in ^{13}C as well as isotopically depleted CO_2. The pool of $\delta^{13}C$ depleted CO_2, while restricted to the hypolimnion during periods of stratification, mixes after overturn and provides an isotopically depleted DIC pool for photoautotrophs in the water column (Hollander and Smith 2001). In a study of sediment cores from Lake Mendota, Wisconsin, Hollander and Smith (2001) attributed depleted $\delta^{13}C$ to the activity of microbial chemoautotrophs and methanotrophs in the hypolimnion and sediments under anoxic conditions. Subsequent studies on cores from eutrophic lakes in Florida (Torres et al., 2012) and Switzerland (Teranes and Bernasconi, 2005) used this process of microbial re-processing of carbon to explain negative-trending $\delta^{13}C$.

Another process which can cause a negative trend in $\delta^{13}C$ relates back to the source carbon pool. Dissolved organic carbon (DOC) in sewage is depleted in the ^{13}C isotope (Burnett and Schaeffer, 1980 and Gearing et al., 1991) and carbon isotope studies of marine and estuarine sewage outfalls have tracked the transmission of sewage-derived carbon through nearby food webs using $\delta^{13}C$ measurements (e.g., Burnett and Schaffer, 1980 and Van Dover et al, 1992). An important mechanism to recognize is that while primary producers use the inorganic carbon pool as a carbon source, as phytoplankton and particularly cyanobacteria uptake the dissolved organic nitrogen (DON) in sewage to acquire nitrogen, the organic molecules containing the depleted ^{13}C are also incorporated (Lindehoff et al., 2009 and Bronk et al., 2007). In separate studies of sediment cores from eutrophic lakes in Florida and Guatemala, Torres et al., 2012 and Rosenmeier et al., 2004 each attributed periods of more negative $\delta^{13}C$ to the incorporation of sewage into lake food webs.

To summarize briefly the controls on $\delta^{13}C$, the isotopic content of organic matter in the water column, and subsequently the sediment is affected both by the source pool of carbon and by photosynthesis itself. Terrestrial carbon inputs can be more enriched and sewage can produce a more negative pool. In terms of primary productivity, under low to moderate productivity, $\delta^{13}C$ can remain unchanged unless the carbon source pool changes. Under moderate to high productivity, $\delta^{13}C$ can increase proportional to productivity. Under hypereutrophic conditions, $\delta^{13}C$ can become more negative due to the influence of heterotrophic activity on the carbon cycle.

The Carbon Isotopic Record of Watson Lake

The carbon isotopic record for Watson Lake is shown in Figures 10 and 11 and a frequency distribution of the carbon isotope data is plotted in Figure 12 with the typical ranges of $\delta^{13}C$ of potential carbon sources. The carbon isotopic record falls into three periods. Prior to the mid-1960s, $\delta^{13}C$ was high and variable, followed by a period of stability until about 1980, and followed then by decline until about 2000. Cores A and B showed different responses from the late-1990s to present, and both cores show a response to the major storm event in 2005.

Prior to the mid-1960s, variable $\delta^{13}C$ may have been due to terrestrial carbon input, which depending on the carbon source (C3 or C4 plants) provided either more enriched or depleted $\delta^{13}C$ than in-lake carbon (Figure 12). As discussed previously, the C/N ratios indicate that organic carbon in Cores A and B is likely composed of a mix of terrestrial and autochthonous carbon, with the greatest proportion of terrestrial matter occurring in the early record. Figure 13 plots C/N versus $\delta^{13}C$ for pre-1964 samples. Particularly in Core B, more depleted $\delta^{13}C$ is associated with higher C/N and presumably terrestrial input. Since the C/N ratios indicated input of terrestrial material, external loading is the likely cause for $\delta^{13}C$ fluctuations.

From the mid-1960s onward, Cores A and B differ somewhat in their $\delta^{13}C$ record, but both cores show a decline in $\delta^{13}C$ until the early-2000s. In the period from the mid-1960s until the early-1980s, both cores show steady $\delta^{13}C$ concentrations, followed by decreasing $\delta^{13}C$. In Core A this decrease continues until the onset of the storm event in 2005. In Core B a similar decrease occurs, but is interrupted by a pulse increase in about 2000. This pulse corresponds to a decrease in total organic carbon and is likely due to erosive deposition of mineral sediments.

Based on the processes described above, this decline could be due to effects of sewage loading or effects on the carbon cycle by benthic heterotrophic activity. Sewage loading has been shown to produce this effect, but is contradicted by the nitrogen isotope record described below. Benthic production of isotopically depleted CO_2 associated with anoxia and methanogenesis is the most likely cause of the decrease in $\delta^{13}C$. The $\delta^{13}C$ decline in Core A was gradual and in Core B occurred much more quickly in the early-1990s.

The major storm event in 2005 affected most analytical parameters measured (Figures 10 and 11). The resolution of the core in this part of the record does not permit detailed analysis of the lake responses. However it does appear that the combination of delivery of mineral sediment combined with flushing, dilution, and some sediment reworking, caused a significant impact on lake sediments.

To summarize interpretations of the carbon isotopic record prior to 2000, the record prior to 1964 shows fluctuating $\delta^{13}C$ influenced by input of terrestrial matter, particularly in Core B. The record from the mid-1960s to about 2000 shows declining $\delta^{13}C$, although the cause of decline is unclear. Possible causes are declining primary productivity, the influence of sewage, or the growing dominance of heterotrophic processes affecting the DIC pool. Sewage and heterotrophic processes are associated with intensifying eutrophication, therefore opposite interpretations of the carbon isotopic record are possible. Additional information is necessary to make conclusive interpretations for this region of the core. The sediment record after about 2000 is characterized by a combination of decreasing $\delta^{13}C$, increasing concentrations of nitrogen and carbon, and increasing N/P. These are consistent with increasing primary productivity and a growing magnitude of the effect of methane production on the carbon budget of the lake, and therefore more intense anoxia, in the lake hypolimion.

Nitrogen Isotopic Processes

Nitrogen stable isotopes can provide insight to a variety of ecosystem processes. Commonly $\delta^{15}N$ measurements are used to infer trophic position in ecosystems, as $\delta^{15}N$ is enriched by 3 to 4 ‰ with each trophic exchange (Peterson and Fry 1986). The phenomenon of $\delta^{15}N$ enrichment through biological processes is shared by both aerobic and anaerobic processes. Denitrification for example results in an enriched pool of remaining nitrate (Hodell and Schelske 1998). Sewage is similarly enriched in $\delta^{15}N$ (Kendall 1998). Detrital terrestrial matter with photosynthetic origins may be relatively depleted in $\delta^{15}N$, and becomes enriched in $\delta^{15}N$ relative to the degree of microbial reprocessing that has occurred (Meyers and Teranes, 2001).

Under nitrogen-limiting conditions the $\delta^{15}N$ content of primary producers can become enriched in $\delta^{15}N$ in the same way that $\delta^{13}C$ becomes enriched. Photosynthetic processes discriminate against the heavy isotope, ^{15}N, resulting in enrichment in the source pool of nitrogen as productivity increases. Under conditions where nitrogen is not limiting, the $\delta^{15}N$ signal reflects the substrate nitrogen pool plus an enriching fractionation factor (Teranes and Bernasconi 2000).

The phenomenon that the $\delta^{15}N$ of an organism reflects its source nitrogen pool draws attention to the substrate nitrogen pool itself. Because most organisms use nitrogen that has been biologically recycled, studies of nitrogen isotopes in ecosystems commonly trace a series of enrichment steps. The one exception is the class of organisms that can fix atmospheric nitrogen. The atmospheric nitrogen pool is well mixed and is perennially set by the definition of the isotope notation at 0.00 ‰. This is a far more depleted value that practically any other nitrogen pool. As a result, the biomass of nitrogen-fixers tends to be more depleted in $\delta^{15}N$ than other organic matter (Teranes and Bernasconi 2005). A number of studies attributed decreasing $\delta^{15}N$ to N-fixing autotrophic processes. Brenner et al. (1999) observed this trend in Florida lakes associated with cyanobacteria. In a study of lakes in a lake in China, Wu et al. (2006) interpreted a trend of increasing $\delta^{15}N$ with productivity under eutrophic conditions. The record then shifted toward more negative $\delta^{15}N$ as the lake made a transition toward hypereutrophy.

Processes related to sediment and water column anoxia can affect the $\delta^{15}N$ record as well. The conversion of nitrate to nitrogen gas forms results in the preferential uptake of ^{14}N, resulting in an enriched pool of remaining nitrate (Hodell and Schelske, 1998). Teranes and Bernasconi (2000) observed higher $\delta^{15}N$ in sediment traps during summer anoxic periods in a Swiss lake and attributed this to enrichment in the DIN pool resulting from denitrification.

Another factor affecting the substrate nitrogen pool is the presence of sewage. Nitrogen in sewage tends to have relatively positive $\delta^{15}N$ (Kendall 1998), thus organisms using sewage-derived nitrogen tend to be enriched in $\delta^{15}N$. In a study of a Guatamalan lake, Rosenmeier et al. (2004) attributed high $\delta^{15}N$ in part of a sediment core to sewage loading to the lake. Torres et al. (2004) made the same interpretation for high $\delta^{15}N$ in a Florida lake, as did Savage (2005) in a study of estuarine sediments in Sweden subject to sewage loading. Lehmann et al. (1997) attributed high $\delta^{15}N$ in sediments to sewage in Lake Lugano on the Swiss, Italian border.

To summarize nitrogen isotopic processes, the N-isotopic signature of sediments reflects the source organic matter. Organisms have a $\delta^{15}N$ content that reflects the nitrogen source plus an enrichment factor of 3 to 4 ‰. For example, phytoplankton with a steady source of nitrogen at 3 ‰ may themselves be expected to have a $\delta^{15}N$ value of 6 or 7 ‰. If the availability of nitrogen becomes limited, the source nitrogen pool may become enriched in $\delta^{15}N$. In this case nitrogen isotopes can be used as a proxy for primary productivity. Other factors that affect $\delta^{15}N$ are denitrification and sewage loading, which result in increased $\delta^{15}N$, or the dominance of nitrogen-fixing organisms which result in decreased $\delta^{15}N$. Nitrogen of terrestrial origin either enriched or depleted $\delta^{15}N$ values, depending on the trophic level of the organic matter.

Nitrogen Transformations in Watson Lake

As with nutrient and carbon isotopic data, the nitrogen isotope record for Watson Lake falls into three periods: variability in the record prior to the mid-1960s, more quiescent conditions from the mid-1960s to about 2000, then change associated with the 2005 storm event toward the top of the core. Prior to the mid-1960s, the N-isotopic record appeared to be dominated by terrestrial inputs. A plot of C/N vs $\delta^{15}N$ (Figure 13 bottom) shows that high C/N prior to the mid-1960s is associated with more depleted $\delta^{15}N$ values, indicating that terrestrial loading had less depleted $\delta^{15}N$.

After the erosive period prior to the mid-1960s, other processes were underway. Considering the sediment nutrient record in Watson Lake (Figures 10 and 11), the increase in total nitrogen relative to total phosphorus could be interpreted as a relaxation of nitrogen limitation and progressive onset of phosphorus limitation. In that case, under conditions of abundant nitrogen, primary producers preferentially uptake ^{14}N in an unlimited N pool, thereby maintaining relatively low $\delta^{15}N$ in the organic matter they produce. In this case the trends of both increasing N and decreasing $\delta^{15}N$ could be interpreted as the progressive relaxation of nitrogen limitation since the 1990s. The problem with this interpretation is that N increases relative to P in the sediment record, not the water-column record. As previously discussed, the increases of N and C relative to P in the sediment indicate a P loss from the sediments to the water column. With abundant phosphate from sediment sources, the lake would indeed become nitrogen limited to such an extent that nitrogen-fixing cyanobacteria would dominate water column primary productivity.

Trends in decreasing $\delta^{15}N$ can be observed in Core A starting in the early-1980s and in Core B starting in the late-1980s. As outlined above, the only processes that can be associated with decreasing $\delta^{15}N$ are influx of terrestrial matter with low $\delta^{15}N$ or influx of atmospheric nitrogen through nitrogen-fixers. The trend in decreasing $\delta^{15}N$ in Core A is coincident with a trend of increasing C/N over roughly the same period, so it is possible that at least some of the decreasing $\delta^{15}N$ can be attributed to a greater loading of terrestrial matter, or perhaps greater loading of detrital organic matter from an expanding Watson Wetlands. However not all of the decreasing trend in $\delta^{15}N$ can be explained by allochthonous material. Figure 13 (bottom) shows that pre-1964 terrestrial material was never observed to be more depleted than about 5 ‰. Post-1964 observations had both low C/N ratios and depleted $\delta^{15}N$ values. This points strongly toward the activity of nitrogen-fixers as dominant in the nitrogen cycle.

An alternative or complementary explanation for decreasing $\delta^{15}N$ is the removal of sewage, a positive source of $\delta^{15}N$. Other researchers have tracked the progressive enrichment of $\delta^{15}N$ in sediments as a result of sewage loading (e.g., Teranes and Bernasconi 2000). The timing of diversion of sewage effluent in the mid-1980s is consistent with the trend shown in Core A data. It is possible that a record of higher $\delta^{15}N$ predated the core records collected for this study. A decrease in $\delta^{15}N$ as a result of removal of a sewage source, directly contradicts an explanation of decreasing $\delta^{13}C$ during this same time period as ongoing source of sewage. Collecting cores at a different location in the lake may result in a longer record which can confirm or disprove this possibility.

Another factor not apparent in Cores A and B is an effect of denitrification. In principle, denitrification results in an enriched pool of remaining nitrate, which then can result in more positive organic matter for consumers of this nitrate. Nitrate concentrations in the sediment tended to be in single-digit parts per million, compared with total nitrogen concentrations in the thousands of ppm. Low nitrate values indicate some combination of a low supply of nitrate through nitrification or the near complete removal of nitrate through denitrification. The anoxic conditions are certainly present in Watson Lake sediments for denitrification. In either case, the nitrate metabolism is apparently not important enough in the lake to result in more positive $\delta^{15}N$ in the sediments.

To summarize the nitrogen isotope record, both cores prior to the mid-1960s indicate loading of terrestrial organic matter, which is consistent with interpretations of the MS, macro-nutrient, and carbon isotope records. Trends of decreasing $\delta^{15}N$ from the early-1980s are consistent with some combination of the removal of a more positive $\delta^{15}N$ sewage source and the progressive importance of cyanobacteria in the nitrogen cycle. The effect of the 2005 storm prevents a conclusive interpretation of the record from about 2000 to 2005, but strongly indicates that Watson Lake was on a trajectory of increased dominance of cyanobacteria.

CONCLUSIONS AND RECOMMENDATIONS

This project consisted of development of a bathymetric map of Watson Lake and the collection and analysis of sediment cores from two locations in the lake (Figure 2). The bathymetric survey provided a digital elevation model for present conditions in the lake to assist in TMDL modeling efforts. Sediment cores were collected in the lacustrine basin (Core A) and riverine basin (Core B) of the lake (Figure 2). Plutonium dating of the cores indicated that coring captured from the late-1940s to present. The depositional environment inferred from the Pu dating and the record of magnetic susceptibility (MS) indicates that sedimentation in the period from the mid-1940s to the mid-1960s was significantly higher than the mid-1960s to present. Climatic changes were ruled out as a cause and improved sediment trapping in the watershed and the development of the Watson Wetlands were presumed to have resulted in lower sedimentation.

Analysis of the cores for nutrient and isotopic parameters revealed several trends in the history of the lake since the mid-1940s. The period from the mid-1940s to the mid-1960s is characterized by high erosion and delivery of allochthonous nutrients to the lake. From the mid-1960s to about 2000, sediments were composed of a mix of terrestrial and in-lake organic matter and three processes seem to be represented in the sediment record in this period: heterotrophic effects on the carbon cycle, effects of sewage loading, and the progressive importance of cyanobacteria in the lake. In the mid-1960s, the lacustrine basin (Site A), $\delta^{13}C$ started a decreasing trend, which is consistent with both increasing influence of methane-producing bacteria in the sediments and hypolimnetic water column. A weak signal for sewage loading may be present in the sediment record, as well. Loading of sewage effluent into the lake, which is known to have occurred until the early-1980s, may have contributed to the decrease in $\delta^{13}C$ observed to start in the mid-1960s. However the trend of decreasing $\delta^{15}N$ starting in the 1980s could be attributed either to the removal of a sewage source, since sewage imprints a more positive $\delta^{15}N$ value on organic matter, or growing dominance of nitrogen-fixing organisms, which results in more negative $\delta^{15}N$. The nitrogen isotopic explanation of sewage contradicts the carbon isotopic explanation and both decreasing $\delta^{13}C$ and decreasing $\delta^{15}N$ can be explained by other processes. Interpreting the parameters together, it is likely that the mid-1960s to about 2000 can be characterized as a period of steadily increasing eutrophication, manifested by increased effects of methane-producing bacteria on the carbon cycle, mild direct effects of sewage, and increased productivity by cyanobacteria. Sewage likely had a stronger indirect effect by supporting decades of primary productivity earlier in the lake's history, leading to the intensely anoxic conditions in the more recent sediments that provide the setting for methanogenesis.

To conclude, the sediment record in Watson Lake since the mid-1940s indicates that the lake has made a transition from a system dominated by external loading of sediments and nutrients to a system that is dominated by internal cycling of nutrients driven by summer hypolimnetic anoxia. Abundant phosphorus supplied by sediments favors primary productivity by cyanobacteria. External loading continues to influence the lake, as indicated by C/N ratios that show a mix of terrestrial and aquatic sources.

With regard to management implications, dredging in the southwestern basin of the lake would remove the sediment accumulated since the mid-1960s and expose more mineral sediment in this zone. This would likely remove the burden of sediment nutrient recycling in this part of the lake. The increase in lake volume may buffer the lake better against changes in concentrations of nutrients and dissolved gases. However unless sediments in deeper zones of the lake are removed or inactivated, the same conditions of anoxic release of phosphorus can be expected to continue in these deeper zones.

Further insights into the sediment record can be derived either by additional analysis of the existing sediment cores or by collecting additional cores as described below.

Additional analyses on existing cores:

- Biogenic silica analysis can provide additional information on primary productivity and may assist in the interpretation of the post-2000 record.
- Particle size analysis and additional Pu analyses on the upper segment of the cores, currently dated as 2000 to 2011, can provide better resolution on the timing of the 2005 storm event.

- Analysis for redox-sensitive elements, such as iron and manganese may be able to provide more information on past redox conditions in the lake.
- Analysis of silver may provide information on urban runoff to the lake. Silver has been used as an indicator of photographic processing waste.
- Analysis of aluminum may provide better insight into terrestrial loading components. Aluminum is normally assumed to erode at a steady rate from watersheds.

Additional cores may provide a longer record into the Watson Lake's past, although there is no guarantee that a longer record can be obtained. Although the lake was impounded in 1919, the depositional environment has been complicated by episodes when the lake has been nearly or completely dry. Many successful coring campaigns have successfully interpreted data through dry periods, or hiatus events, but these events add complexity to interpretations.

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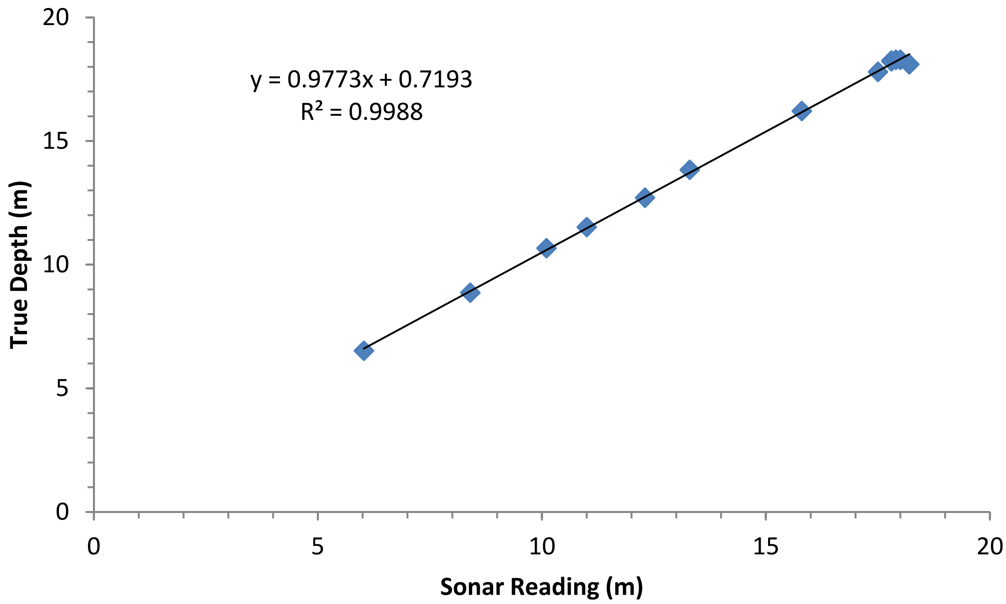


Figure 1. Calibration of sonar-determined depths.
Source: Spreadsheets / Figure 01 – Calibration.xlsx

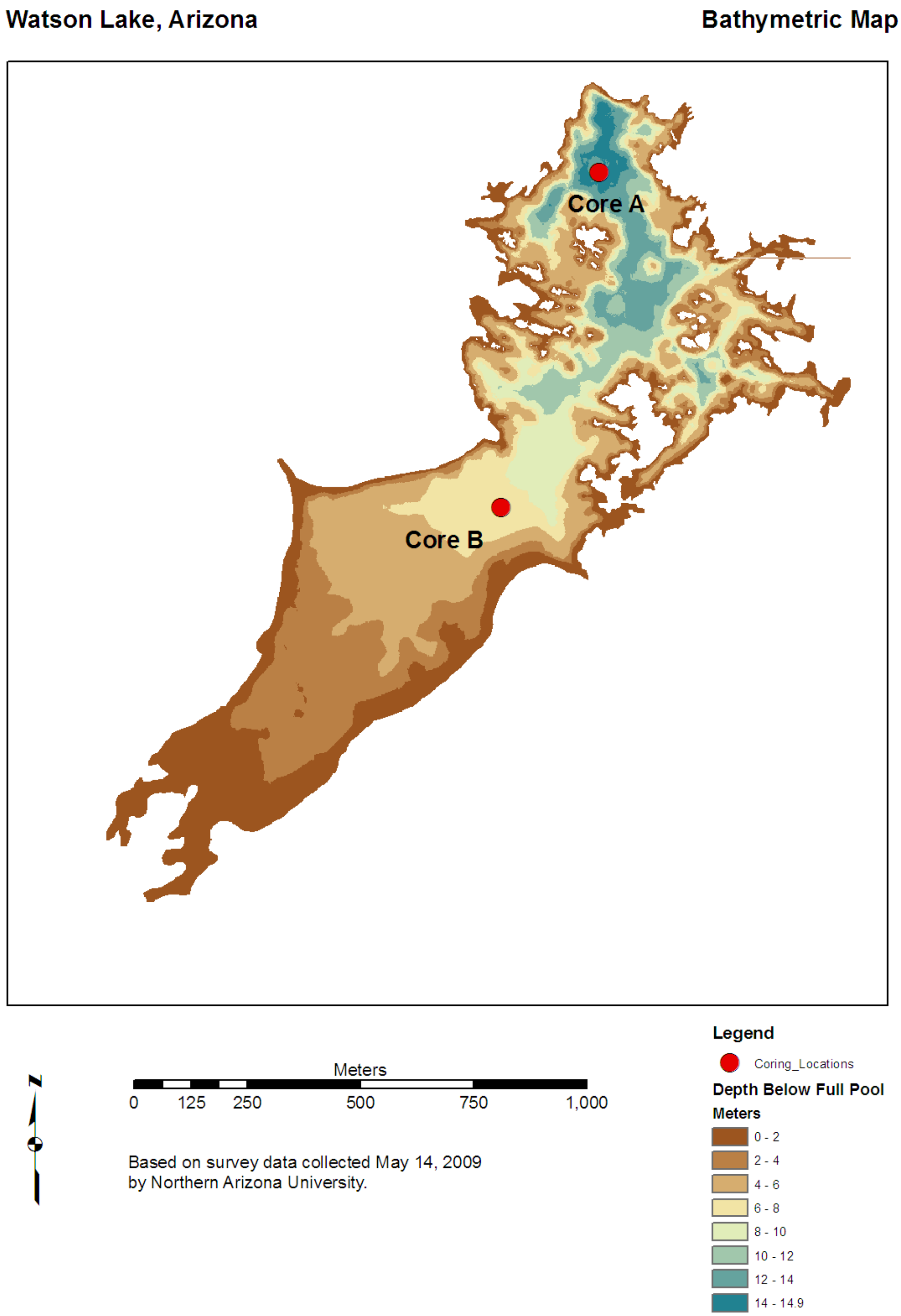
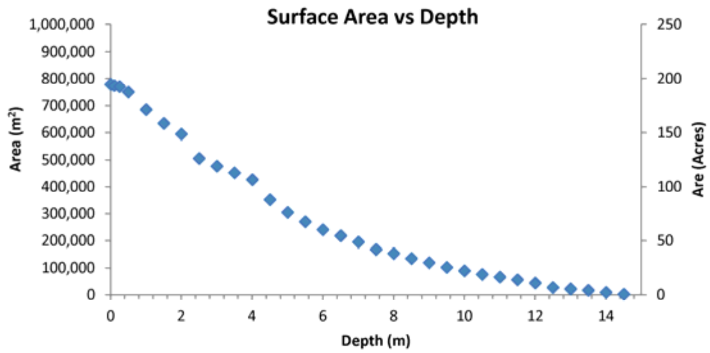
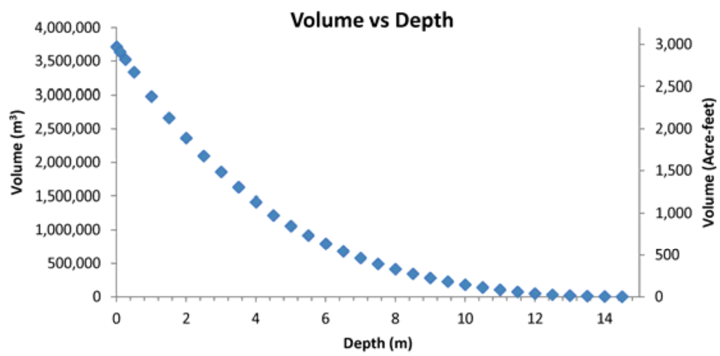


Figure 2. Watson Lake bathymetry and coring locations.
Source: Bathymetry / Maps / Watson Bathymetry.pdf





Depth (m)	Area (m^2)	Volume (m^3)	Area (acres)	Volume (acre-feet)
0.0	778,918	3,711,766	192.5	3,009.2
0.1	774,147	3,635,759	191.3	2,947.6
0.3	770,734	3,522,074	190.5	2,855.4
0.5	750,725	3,334,854	185.5	2,703.6
1.0	684,889	2,982,754	169.2	2,418.2
1.5	633,897	2,662,791	156.6	2,158.8
2.0	594,522	2,361,815	146.9	1,914.8
2.5	505,662	2,094,495	125.0	1,698.0
3.0	476,415	1,855,588	117.7	1,504.3
3.5	452,160	1,628,892	111.7	1,320.6
4.0	426,422	1,414,142	105.4	1,146.5
4.5	351,918	1,215,810	87.0	985.7
5.0	304,379	1,057,269	75.2	857.1
5.5	269,733	917,748	66.7	744.0
6.0	240,354	793,418	59.4	643.2
6.5	218,008	681,737	53.9	552.7
7.0	194,968	580,669	48.2	470.8
7.5	167,622	492,336	41.4	399.1
8.0	152,862	413,929	37.8	335.6
8.5	134,461	343,483	33.2	278.5
9.0	119,377	281,200	29.5	228.0
9.5	101,801	226,511	25.2	183.6
10.0	89,534	179,643	22.1	145.6
10.5	76,287	138,755	18.9	112.5
11.0	66,125	103,858	16.3	84.2
11.5	56,283	73,423	13.9	59.5
12.0	43,929	48,477	10.9	39.3
12.5	27,271	31,235	6.7	25.3
13.0	21,906	19,280	5.4	15.6
13.5	16,951	9,558	4.2	7.7
14.0	9,145	3,049	2.3	2.5
14.5	2,310	446	0.6	0.4

Figure 3. Plots and table of surface area and volume as functions of depth below full pool.
Souce: Spreadsheets / Figure 03 – Depth Area Volume.xlsx

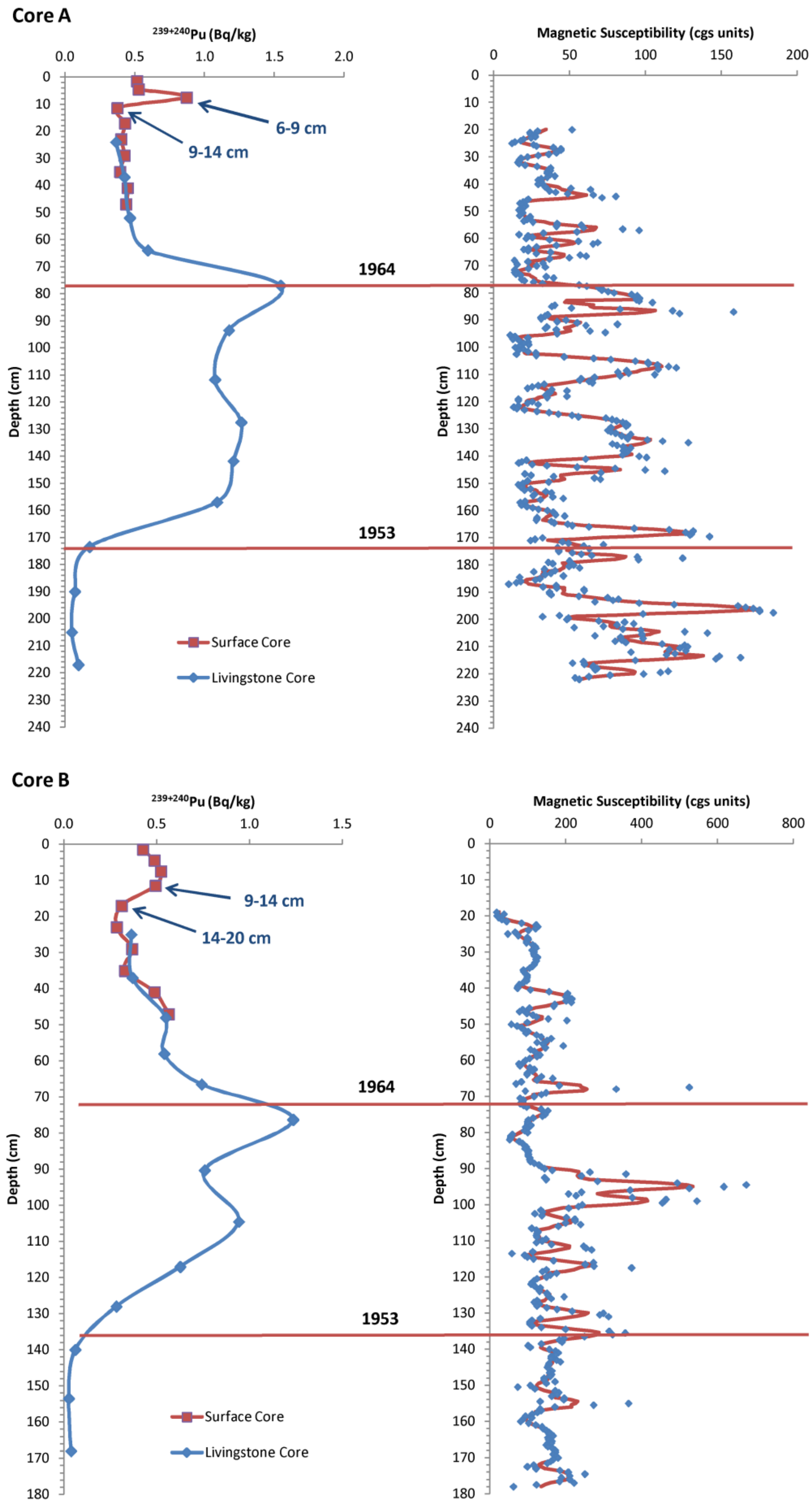


Figure 4. Plots of plutonium and magnetic susceptibility.
Source: Spreadsheets / Watson Data.xlsx, Worksheet = Chronometry Analysis

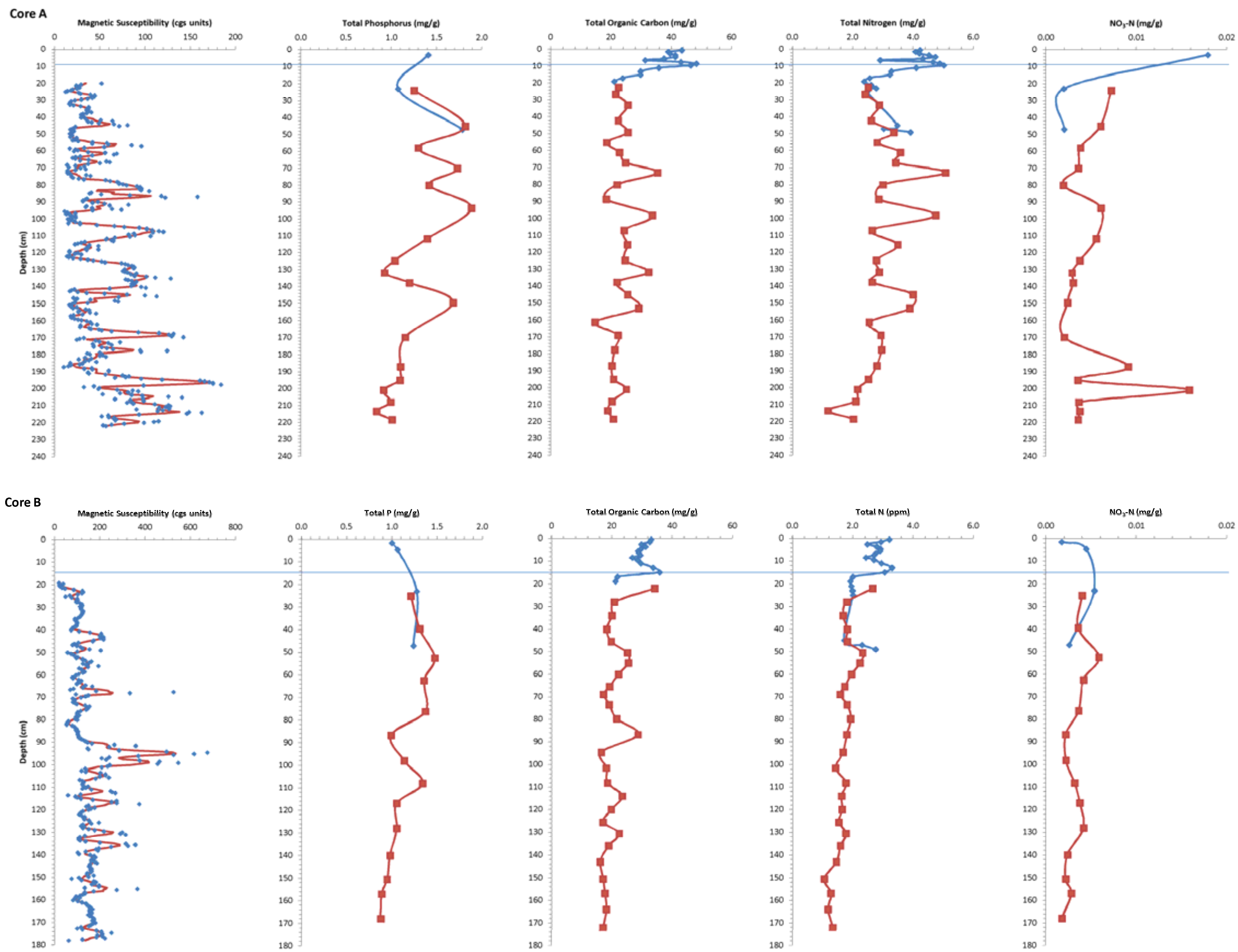
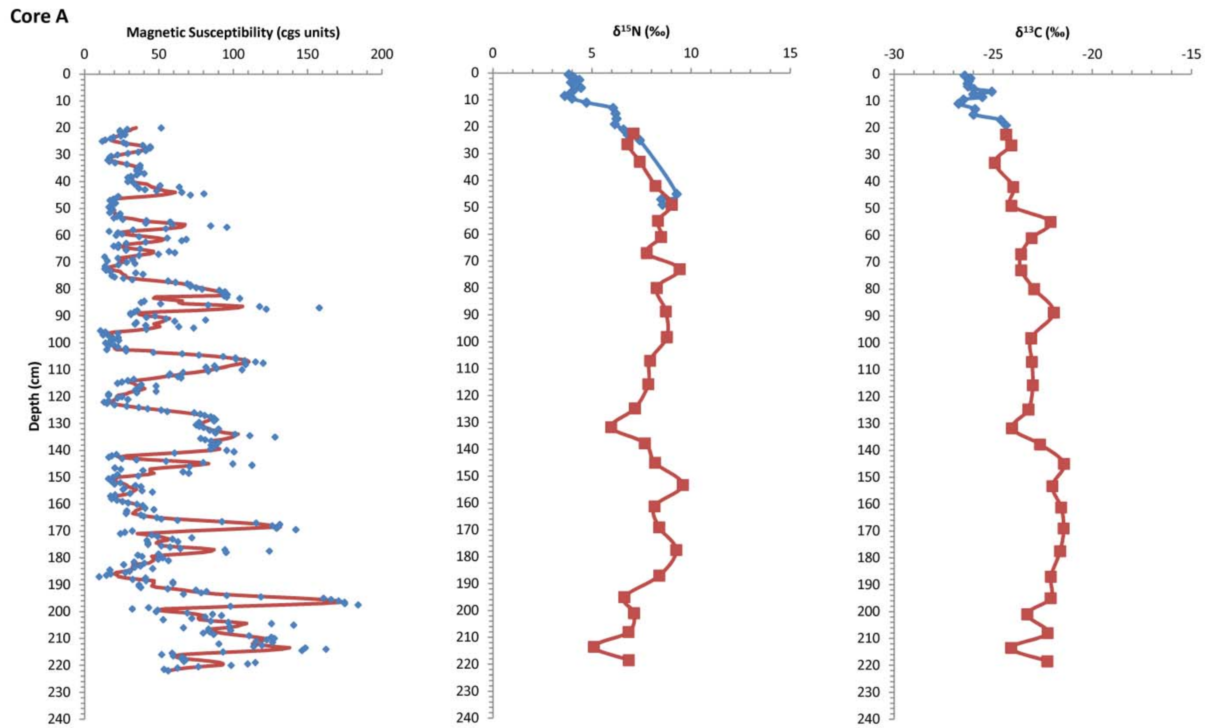


Figure 5. Plots of nutrient data in Cores A and B.

Source: Spreadsheets / Watson Data, Worksheet = Nutrient Plots v Depth



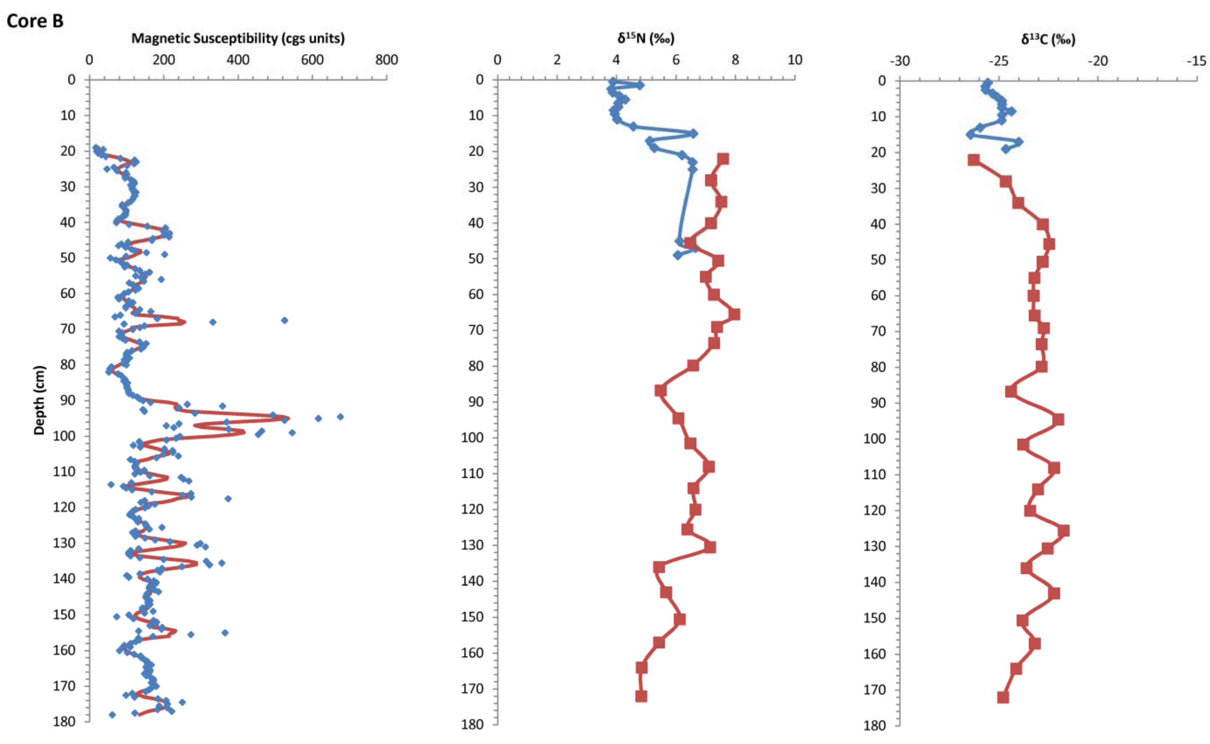


Figure 6. Isotope plots versus depth.

Source: Spreadsheets / Watson Data.xlsx, Worksheet = Isotope Plots v Depth

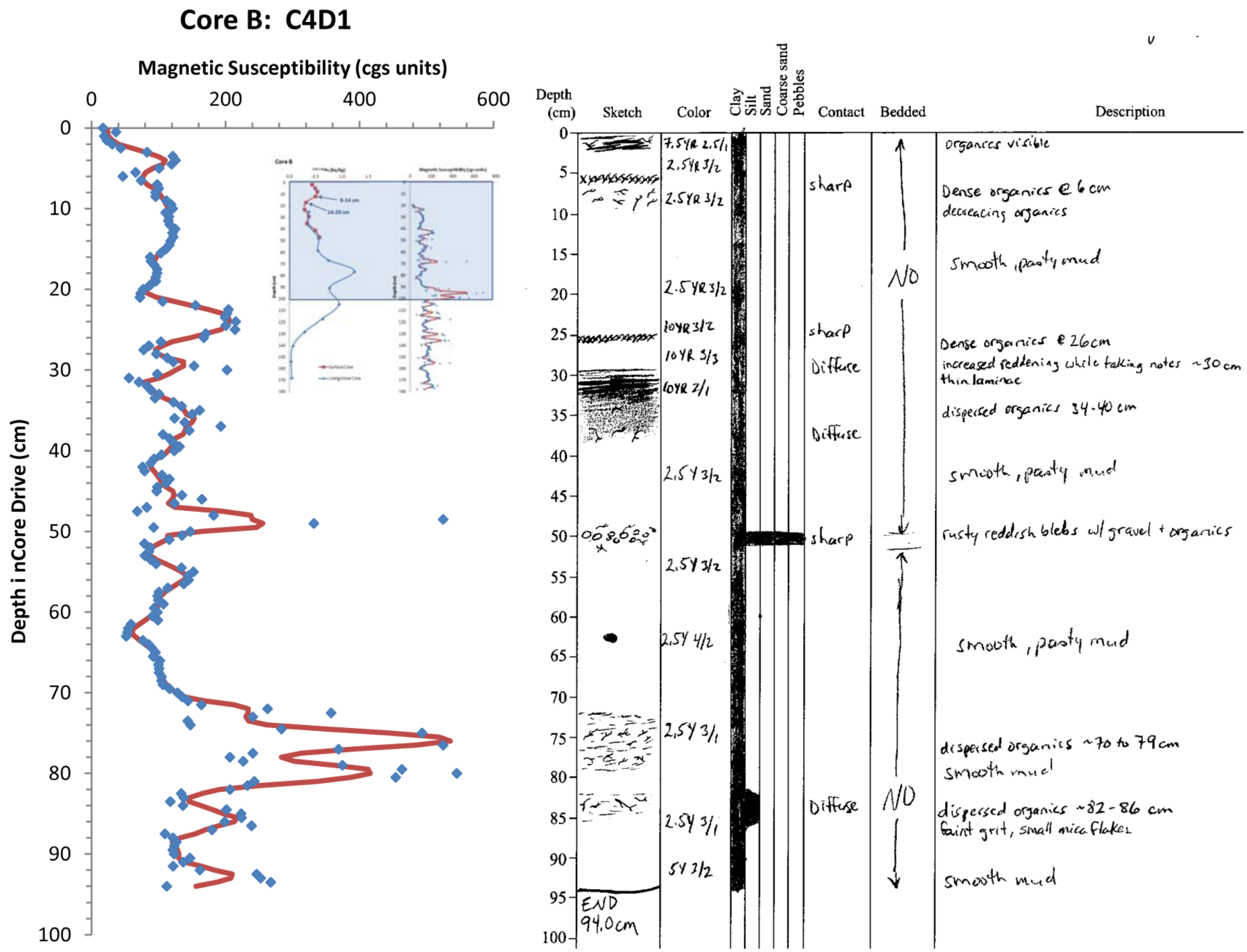
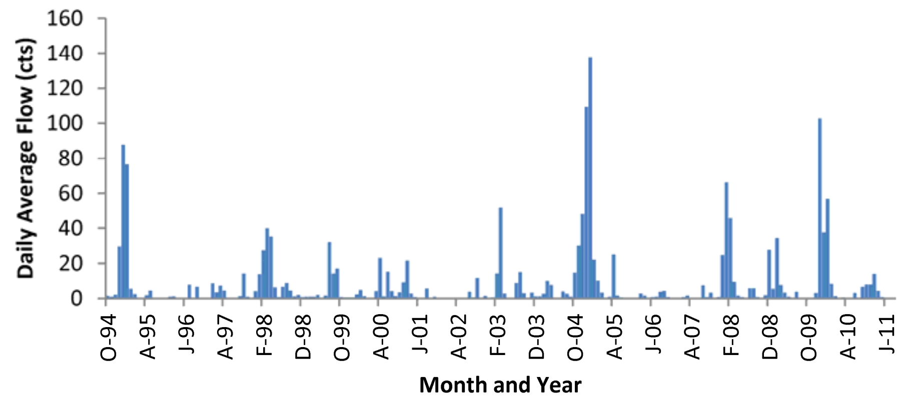


Figure 7. Lithologic log and magnetic susceptibility record of Core B, Core 4, Drive 1.
Source: Figure Files / Core Lithology Figure.pptx



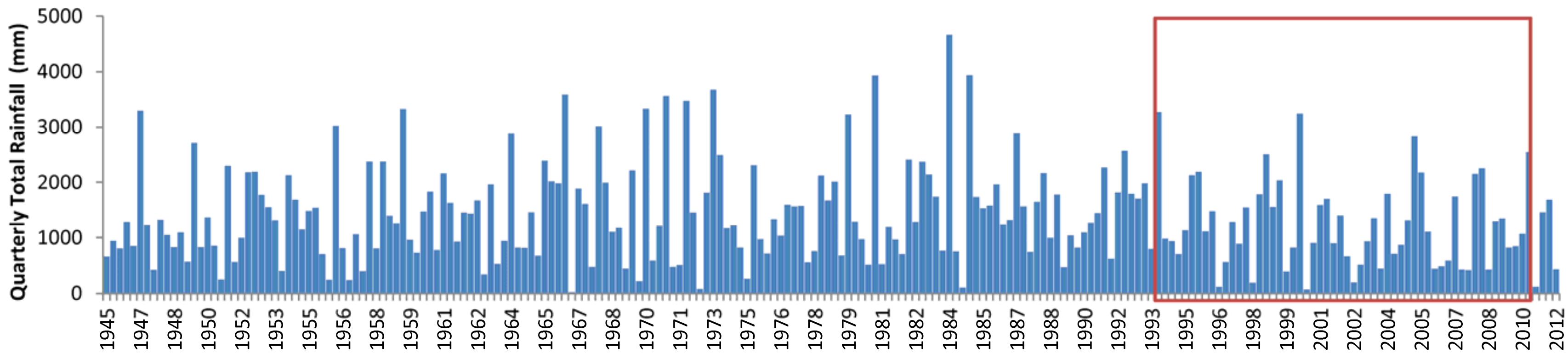


Figure 8. Precipitation and flow data, 1945 to 2011.
Source: Figure Files / Flow and Precip Plots.pptx and Prescott Precip 2012-04-03.xslx

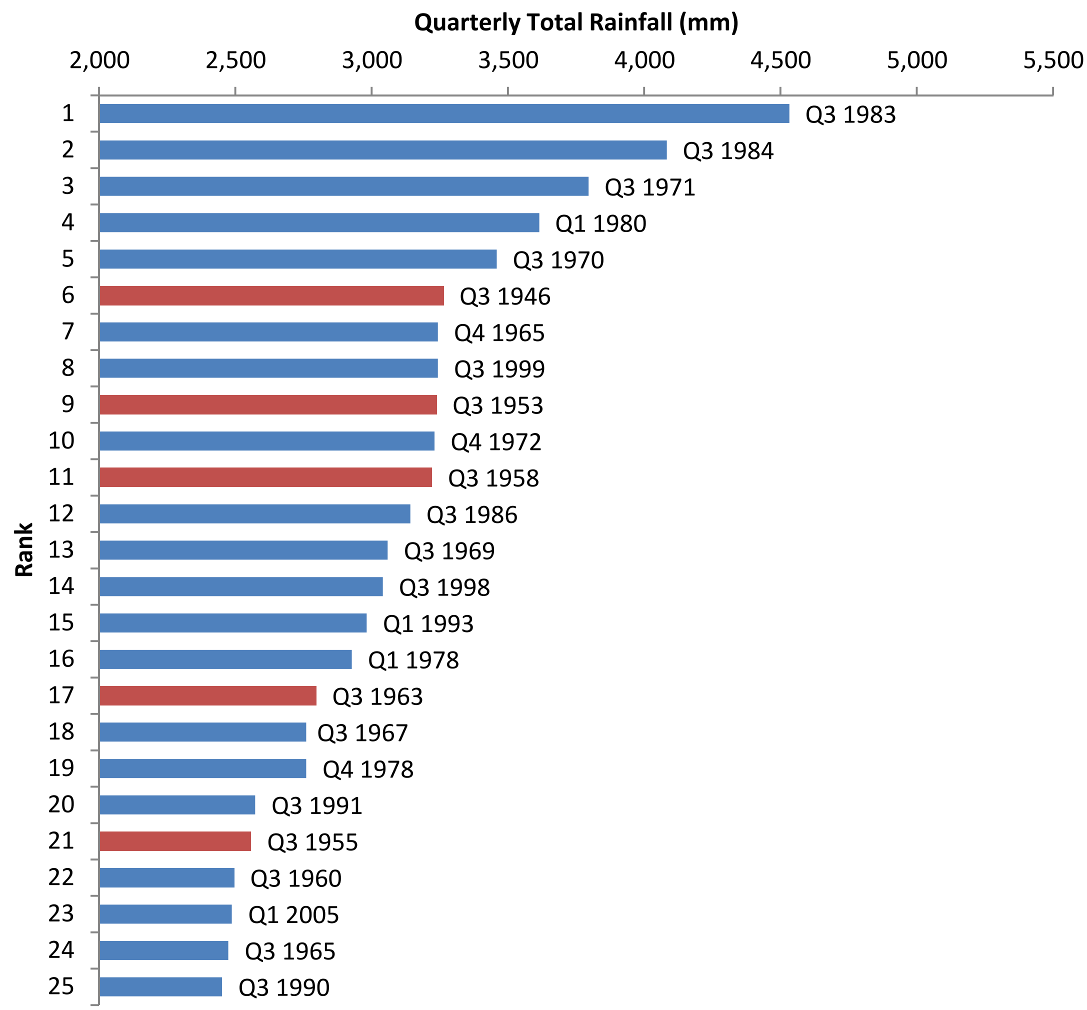


Figure 9. Ranking of quarterly total precipitation at Prescott, Arizona from 1945 to 2011. Blue bars indicate quarters after 1964 and red bars indicate quarters including and before 1964.
Source: Spreadsheets / Prescott Precip 2012-04003.xlsx

CORE A -- Near Dam

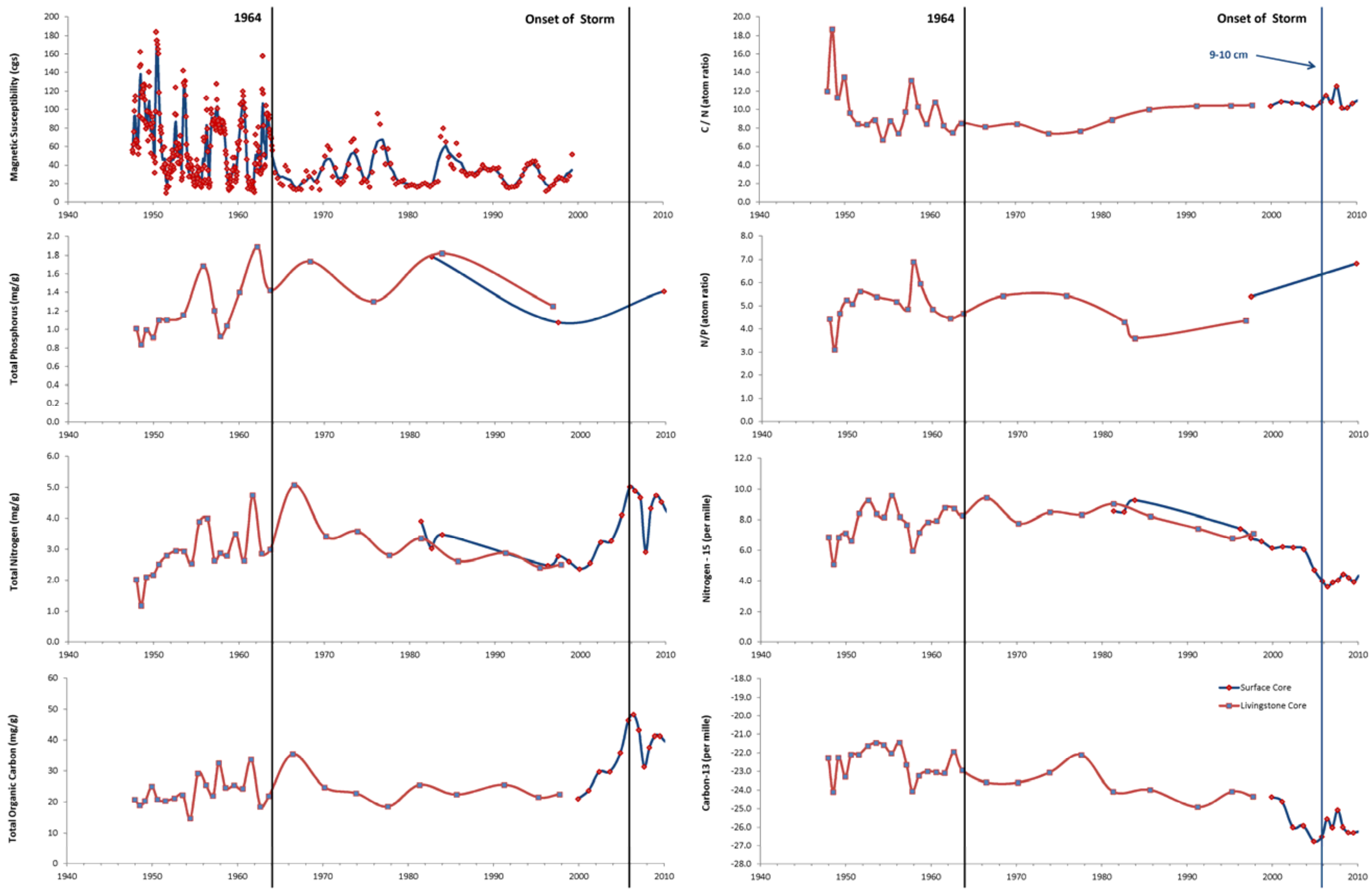


Figure 10. Analytical data from Watson Lake, Core A, plotted versus time.
Source: Spreadsheets / Watson Lake Data.xlsx, Worksheet = Plots v Time

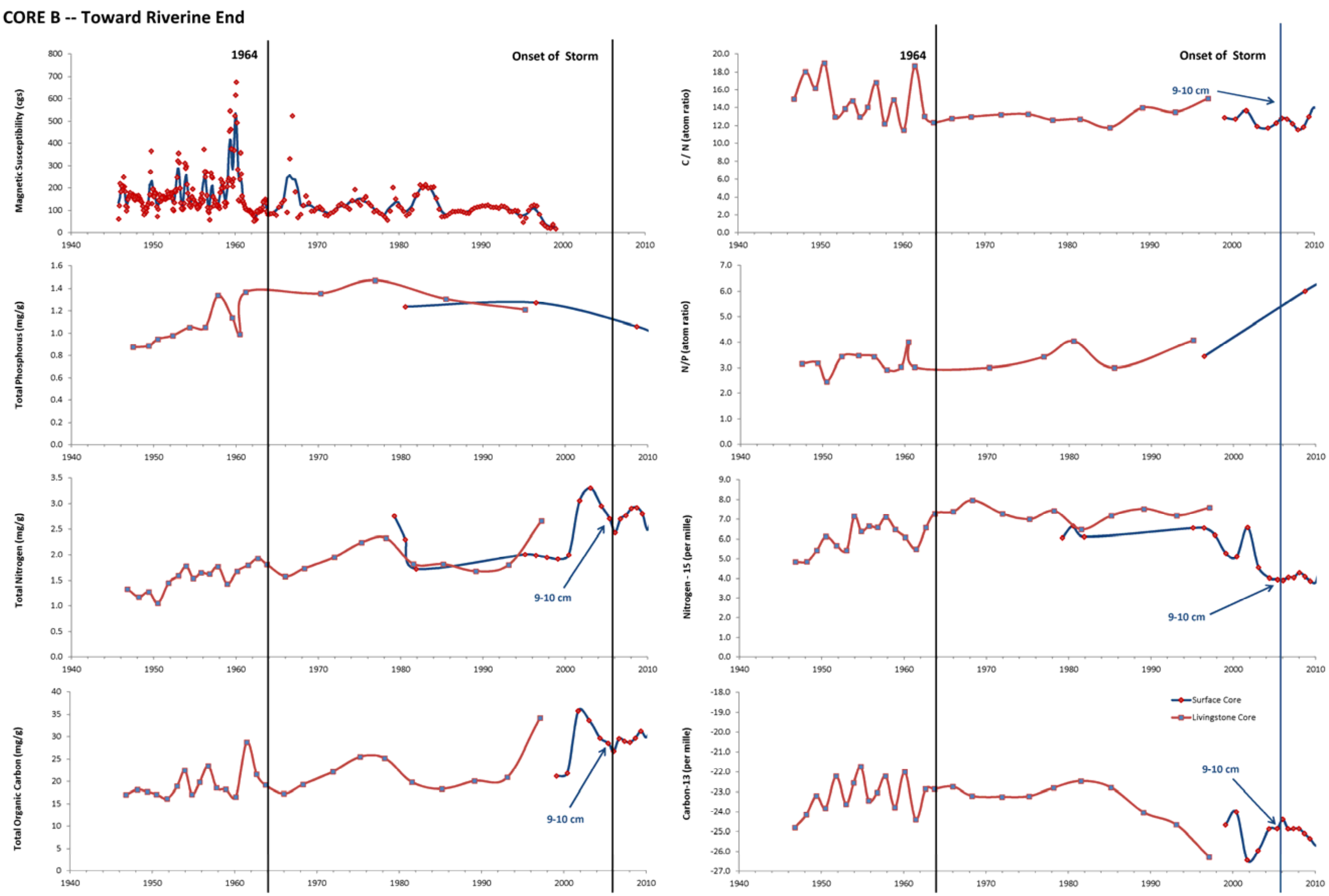


Figure 11. Analytical data from Watson Lake, Core B, plotted versus time.
Source: Spreadsheets / Watson Lake Data.xlsx, Worksheet = Plots v Time

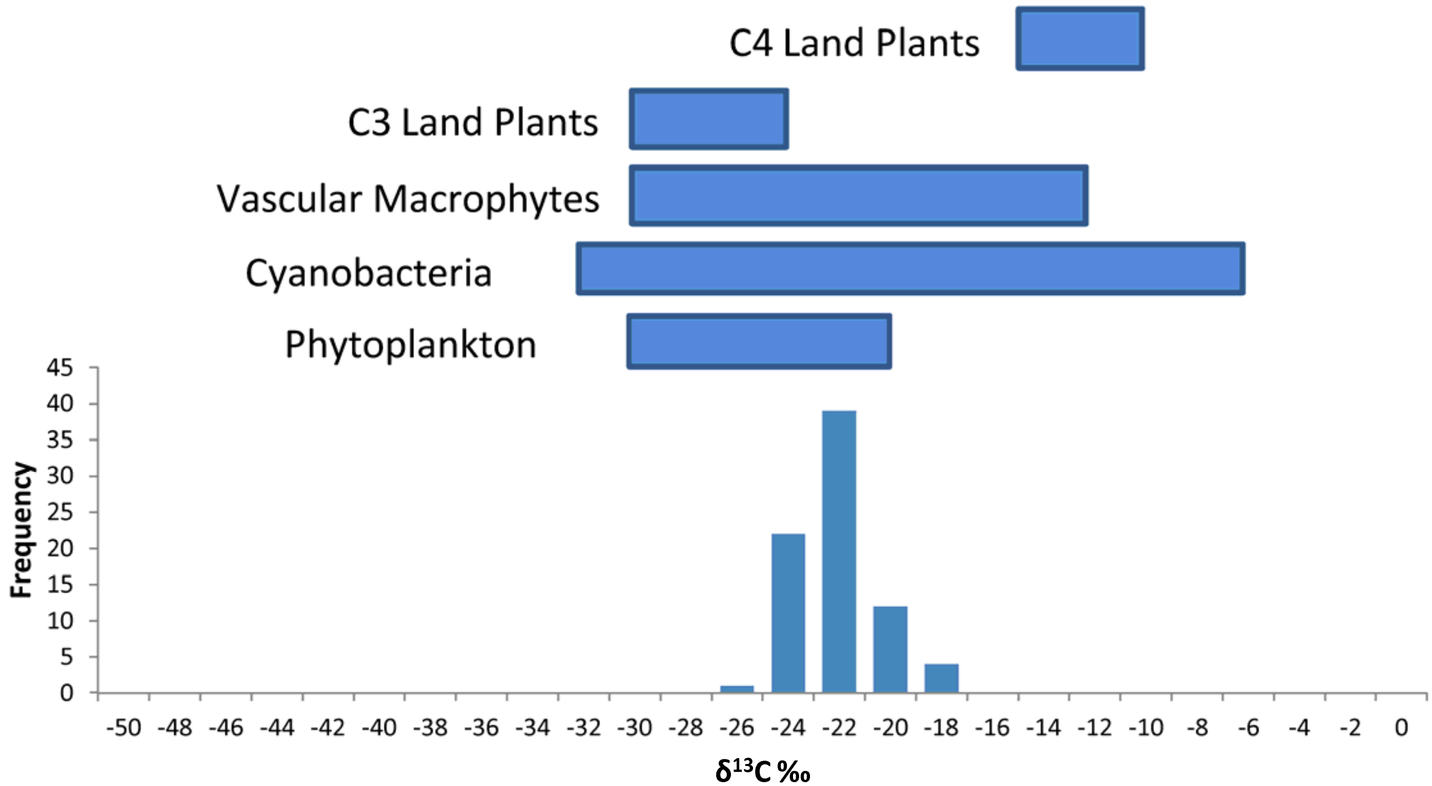


Figure 12. Histogram of carbon isotope observation with typical ranges of isotopic content of carbon sources.
Source: Spreadsheets / Watson Lake Data.xlsx, Worksheet = Plots v Time

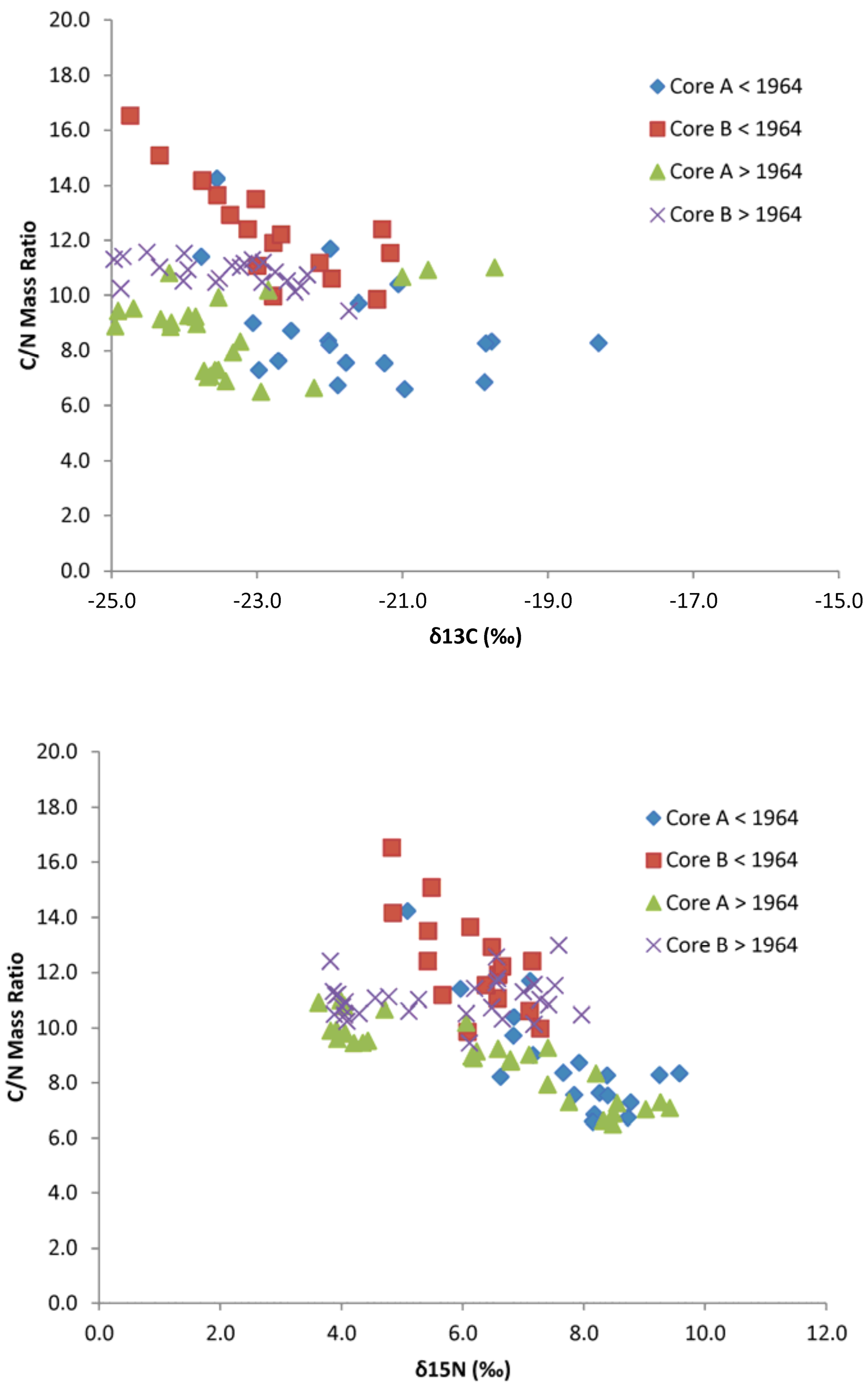


Figure 13. C/N ratio vs $\delta^{13}C$ (top) and $\delta^{15}N$ (bottom) for pre-1964 and post-1964 samples.

TABLE 1. Statistical Summary of Analytical Data.

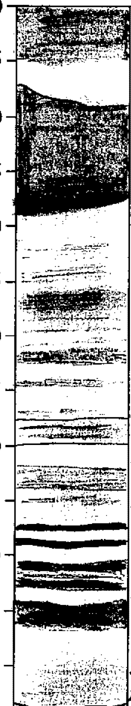
Parameter	Units	Core	n	mean	stdev	min	max
Magnetic Susceptibility	cgs	A	404	55	36	10	184
		B	319	153	88	17	675
Total Phosphorus	ppm	A	21	1,287	327	838	1,888
		B	18	1,141	183	874	1,471
Total Carbon	%	A	49	2.87	0.96	1.67	5.52
		B	47	2.37	0.61	1.44	3.65
Total Nitrogen	ppm	A	49	3,266	901	1,179	5,072
		B	47	2,089	587	1,051	3,297
Nitrate Nitrogen as N	ppm	A	21	4.99	2.36	1.98	9.93
		B	18	3.32	1.20	1.71	5.84
Carbon-13 ($\delta^{13}C$)	‰	A	49	-22.90	1.72	-25.78	-18.31
		B	47	-23.51	1.27	-26.17	-21.17
Nitrogen-15 ($\delta^{15}N$)	‰	A	49	6.85	1.80	3.62	9.58
		B	47	5.86	1.26	3.81	7.96

CORE DESCRIPTION SHEET

Location: Watson Lake State: AZ Lat: ________ Long: ________

Date Collected: ____________ Core Type: Livingston

Core : 2 Drive: 1 Date Logged: Oct 1, 2011 Logger: ABright

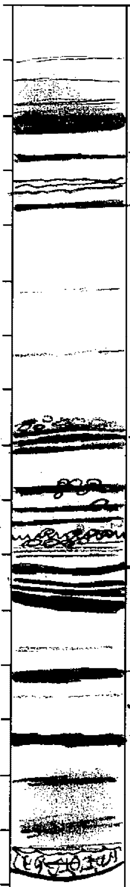
Depth (cm)	Sketch	Color	Clay / Silt / Sand / Coarse sand / Pebbles	Contact	Bedded	Description
0		7.5YR 2.5/1				Entire length is smooth pasty mud
5		2.5Y 4/2		diffuse	NO	top 3 cm is disturbed
10		↑ 7.5YR 2.5/1		sharp		
15		↓		sharp		
20		2.5Y 4/2				Smooth mud
25						
30		2.5Y 4/1				
35		2.5Y 4/1, 2.5Y 6/3, 2.5Y 5/3, 2.5Y 6/3, 2.5Y 5/3		Diffuse		} distinct section w/ ligher tan grading to darker brown } 2 cycles
40		2.5Y 4/2, 2.5Y 4/2		Diffuse		
45		2.5Y 4/2		Diffuse		
50		7.5YR 2.5/1, 10YR 5/2, 10YR 5/2, 7.5YR 2.5/1		sharp, sharp		
55		10YR 5/2, 7.5YR 2.5/1		sharp, diffuse		Smooth mud
60		2.5Y 5/2, 2.5Y 3/2				
65	End 63.5cm	2.5Y 3/1			NO	
70						
75						
80						
85						
90						
95						
100						
105						
110						

CORE DESCRIPTION SHEET

Location: Watson Lake State: AZ Lat: ________ Long: ________

Date Collected: ____________ Core Type: Livingston

Core: 2 Drive: 2a Date Logged: Oct 1, 2011 Logger: JBright



Depth (cm)	Color	Contact	Bedded	Description
~4	10YR 3/2, 10YR 4/2	diffuse	↑	smooth, pasty mud
~8	10YR 3/2			
~10	7.5YR 2.5/1	diffuse	ND	
~12	10YR 4/2			
~13	7.5YR 2.5/1	sharp		
~16	10YR 5/2	sharp		thin laminae 16-18cm ; rocks
~18	7.5YR 2.5/1	diffuse		
~20	10YR 5/2 ↓ grade			rocks? ~20cm
~25	10YR 3/2	diffuse		
~27	10YR 3/1 ↓ grade			
~30	10YR 3/1	diffuse		Smooth, pasty mud ; possibly some very fine organics 26-31cm
~33	10YR 5/2 ↓ grade			
~37	10YR 3/1		ND	rusty reddish blebs @ 38cm, smooth pasty texture; thin light banding in black unit
~40		sharp		
~42	10YR 5/2			rusty reddish blebs @ 44 + 46cm ; smooth + pasty
~45	10YR 5/2	sharp		
~48 (broken)				Broken @ 48cm, rusty blebs at + above break ; smooth, pasty
~50	10YR 5/2			thin laminae @ ~49cm
~53		sharp		
~55	7.5YR 2.5/1, 10YR 5/2			Smooth pasty mud
~60	10YR 5/2, 7.5YR 2.5/1, 10YR 5/2		ND	
~63		diffuse		increased reddening 63.5-67cm while making notes
~64	7.5YR 3/4			
~66		sharp		
~67	7.5YR 2.5/1			
~69	10YR 5/2			
~71		diffuse		smooth pasty mud ↓
~73	10YR 4/2			
~75	10YR 4/2	diffuse		
~78	10YR 3/3		ND	Base is chunky. Can't smooth it out. Smooth texture but very sticky.

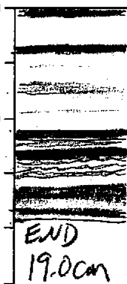
END 79.5cm

CORE DESCRIPTION SHEET

Location: Watson Lake State: AZ Lat: ______ Long: ______

Date Collected: ______ Core Type: Livingston

Core: 2 Drive: 2b Date Logged: Oct 1, 2011 Logger: J Bright



Depth (cm)	Color	Clay	Silt	Sand	Coarse sand	Pebbles	Contact	Bedded	Description
0	7.5YR 2.5/1 7.5YR 3/3	■					Sharp	↑	Soft smooth mud for entire length.
5	7.5YR 2.5/1 10 YR 4/2 10 YR 5/2 (7.5YR 2.5/1) 10YR 5/2	■					Sharp Diffuse		gradational color changes 4-7cm, 8-11 cm
10	10YR 4/2 7.5YR 2.5/1 7.5YR 2.5/1	■					sharp wavy	NO	smooth
15	7.5YR 2.5/1	■					diffuse diffuse	↓	thin, grey/black wavy laminae 14-15cm smooth
20									
25									
30									
35									
40									
45									
50									
55									
60									
65									
70									
75									
80									
85									
90									
95									
100									
105									
110									

CORE DESCRIPTION SHEET

Location: Watson Lake State: AZ Lat: ______ Long: ______

Date Collected: ______ Core Type: Livingston

Core: 2 Drive: 3 Date Logged: Oct. 1, 2011 Logger: J Bright

Depth (cm)	Color	Contact	Bedded	Description
0–10	10YR 3/3 and 10YR 2/1	diffuse	|	smooth texture but very sticky to ~10 cm hint of oxidation (rusty red) and black blebs. sticky ↓
10–17	10YR 3/1		No	smooth, pasty mud
17–21	7.5YR 2.5/1, 10YR 3/1, 7.5YR 2.5/1	sharp, sharp	|	slight grit / textural change @ 20cm; fine mica flecks
21–30	10YR 3/1		No	smooth pasty mud
30–35	10YR 5/6	gradational, sharp		coarsening downward from ~31 to 34 cm. Coarse sand clearly visible at base of unit.
35–40	10YR 3/1		|	smooth, pasty mud; mica flecks at base of core section; thin sandy layer at very base

END 40.0 cm

CORE DESCRIPTION SHEET

Location: Watson Lake State: AZ Lat: ________ Long: ________

Date Collected: ____________ Core Type: Livingston

Core : 4 Drive: 1 Date Logged: Oct. 1, 2011 Logger: [signature]

Depth (cm)	Color	Contact	Bedded	Description
0	7.5YR 2.5/1			organics visible
3	2.5YR 3/2			
6		sharp		Dense organics @ 6 cm
8–10	2.5YR 3/2			decreasing organics
15–20	2.5YR 3/2		NO	smooth, pasty mud
25	10YR 3/2	sharp		Dense organics @ 26cm
28–30	10YR 5/3	Diffuse		increased reddening while taking notes ~30 cm thin laminae
32	10YR 2/1			
35				dispersed organics 34-40 cm
38		Diffuse		
42	2.5Y 3/2			smooth, pasty mud
50		sharp		rusty reddish blebs w/ gravel + organics
54	2.5Y 3/2			
64	2.5Y 4/2			smooth, pasty mud
75	2.5Y 3/1			dispersed organics ~70 to 79 cm
80				smooth mud
84		Diffuse	NO	dispersed organics ~82-86 cm
86	2.5Y 3/1			faint grit, small mica flakes
91	5Y 3/2			smooth mud
94	END 94.0cm			

Core	Depth in Core (cm)	Relative Depth (cm)	Absolute Depth (cm)	Samples Collected	Pu Samples	Isotope, C, and N	Total P, Nitrate
C2D1	0.0	0.0	15.0				
	0.5	0.5	15.5				
	1.0	1.0	16.0				
	1.5	1.5	16.5				
	2.0	2.0	17.0				
	2.5	2.5	17.5	S 25		I 25	
	3.0	3.0	18.0				
	3.5	3.5	18.5				
	4.0	4.0	19.0		P 21		
	4.5	4.5	19.5				
	5.0	5.0	20.0				
	5.5	5.5	20.5				
	6.0	6.0	21.0				
	6.5	6.5	21.5	S 26		I 26	
	7.0	7.0	22.0				
	7.5	7.5	22.5				
	8.0	8.0	23.0				
	8.5	8.5	23.5				
	9.0	9.0	24.0				N 08
	9.5	9.5	24.5				
	10.0	10.0	25.0				
	10.5	10.5	25.5				
	11.0	11.0	26.0				
	11.5	11.5	26.5				
	12.0	12.0	27.0				
	12.5	12.5	27.5				
	13.0	13.0	28.0	S 27		I 27	
	13.5	13.5	28.5				
	14.0	14.0	29.0				
	14.5	14.5	29.5				
	15.0	15.0	30.0				
	15.5	15.5	30.5				
	16.0	16.0	31.0				
	16.5	16.5	31.5				
	17.0	17.0	32.0		P 22		
	17.5	17.5	32.5				
	18.0	18.0	33.0				
	18.5	18.5	33.5				
	19.0	19.0	34.0				
	19.5	19.5	34.5				
	20.0	20.0	35.0				
	20.5	20.5	35.5				
	21.0	21.0	36.0				
	21.5	21.5	36.5				
	22.0	22.0	37.0	S 28		I 28	

	22.5	22.5	37.5	S 28		I 28	
	23.0	23.0	38.0				
	23.5	23.5	38.5				
	24.0	24.0	39.0				
	24.5	24.5	39.5				
	25.0	25.0	40.0				N 09
	25.5	25.5	40.5				
	26.0	26.0	41.0				
	26.5	26.5	41.5				
	27.0	27.0	42.0				
	27.5	27.5	42.5				
	28.0	28.0	43.0				
	28.5	28.5	43.5				
	29.0	29.0	44.0	S 29		I 29	
	29.5	29.5	44.5				
	30.0	30.0	45.0				
	30.5	30.5	45.5				
	31.0	31.0	46.0				
	31.5	31.5	46.5				
	32.0	32.0	47.0		P 23		
	32.5	32.5	47.5				
	33.0	33.0	48.0				
	33.5	33.5	48.5				
	34.0	34.0	49.0				
	34.5	34.5	49.5				
	35.0	35.0	50.0	S 30		S 30	N 10
	35.5	35.5	50.5				
	36.0	36.0	51.0				
	36.5	36.5	51.5				
	37.0	37.0	52.0				
	37.5	37.5	52.5				
	38.0	38.0	53.0				