

**Linking the Effects of Land Use vs. Changing Climate on Water Quality in
Ossipee and Squam Lakes, NH**

AN ABSTRACT OF THE THESIS OF

Melanie M. Perello for the degree of Master of Science in Environmental Science and Policy presented on Defense Date.

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With water quality as a key issue in water resource management, the need to understand the impacts of land use and climate on freshwater systems has never been greater. Lakes are particularly responsive to watershed changes, many of which are ephemeral, captured only by continuous monitoring. Lake sediments continuously record and archive lake conditions, potentially filling gaps in monitoring datasets. This study aims to identify transient, sub-annual changes in sedimentary archives, using integrated data from lake water chemistry, sediment traps and sediment cores in two northern lakes: Ossipee and Squam, NH. We compare our findings with documented records of local land use and climate change to determine how these manifest in our lake records. Our resulting time series include water column data for temperature, dissolved oxygen, major ions and phosphorus in depth profiles in every season, and a sedimentary time series, extending to pre-Colonial times, which includes ^{210}Pb activity, particle size, diatom community assemblages, and mineral chemistry. We use PCA and CA to identify sediment variables closely associated with water quality, climate, and land use indicators, which is then used to inform local community stakeholders on potential impacts of watershed changes.

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Lakes, NH

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Melanie M. Perello

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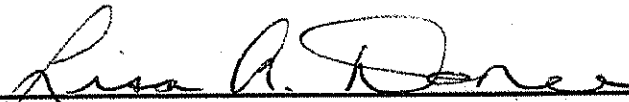
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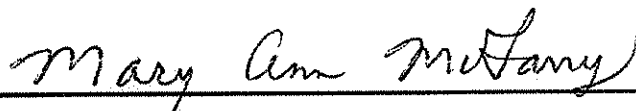
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Introduction

Increases in demand for safe, clean water due to growing human populations and increases in daily usage, combine with depletions and degradations of water resources throughout the world to enhance the urgency for protection of these resources (Vörösmarty et al., 2000). This need has resulted in resource managers giving water quality a higher precedence than in the past. This shift in focus towards protection of resource quality has prompted some governments to regulate pollution of surface waters and mandate remediation efforts of impaired lakes, wetlands and rivers. The Clean Water Act (CWA) of 1972 is the foundation for water protection in the United States (Salzman and Thompson, 2010). Overseen by the Environmental Protection Agency (EPA), the CWA requires water bodies to be designated for particular uses, *ie.* drinkable or fishable waters, which then correspond to specific standards for water quality (Salzman and Thompson, 2010). With water quality protection, monitoring, and conservation primary concerns for managers, there is growing need to understand and anticipate the causes of degradation and the avenues by which undesirable changes are mitigated. My overall goal is to better connect climate issues with water quality, because changing climate may have significant impacts on our aquatic resources. Informing lake management and conservation groups of how lakes are affected by climate change will help them better manage these resources and where to focus mitigation efforts in the future.

Of all surface bodies of water, lake systems are particularly vulnerable to impacts from their surrounding environment. Lakes are sentinels for change in their watersheds, with high residence times that take longer to recover from quality declines (Schindler, 2009). Because they often serve as drinking water reservoirs and can be a source of revenue from recreation and property taxes, lakes are also important resources for communities. Ecologically, lakes provide vital habitat for a variety of organisms, ranging from primary producers to fish to birds. Lakes that are typically part of closed or semi-closed hydrologic systems form excellent models with which to study environmental change in their respective watersheds. For lakes situated at low elevations, runoff from the surrounding uplands carries with it materials representative of the surrounding watershed and deposits from the airshed (Schindler, 2009). These are deposited in the lakes and are subsequently focused in thick accumulations in the deepest basins. Sediment cores of these deep basins provide continuous records, over historical timelines, of environmental conditions within the lake and its watershed (Smol, 2010).

Lake water quality decline can be attributed to a number of factors including: nutrient pollution from non-point sources, which are under-regulated by the CWA; surrounding watershed land use; and changing climate. Most studies of water quality focus on nutrient pollution due to its large scale impacts, particularly in more populated areas (Robertson and Saad, 2011, Smith et al., 2006). In most regions of the U.S. land use has changed significantly within the past two hundred years, historically with large scale land clearances for logging and agriculture, and in recent years, with a move towards a more spread out, large human population (Thompson et al., 2013). During this same period, most regions of the U.S. have experienced changing climate trends, particularly in temperature and precipitation (Griffiths and Bradley, 2007).

These combined impacts are likely to have a great impact on surface water degradation.

With the interconnected relationship between climate conditions and water quality, research into past climate conditions can address questions about long-term and ongoing lake conditions. Lake ecosystems are very susceptible to atmospheric and terrestrial changes and are strongly influenced by climate, seasonal changes in precipitation, and human-disturbances (Queimaliños et al., 2012, Schindler, 2009, Williamson et al., 2009). Greater understanding of the relationship between climate and water quality prepares managers to predict and mitigate future water quality issues with changing climate conditions. This study assesses both current and past lake functioning with emphasis on climate and water quality. Combining limnological and paleolimnological techniques, I endeavor to provide lake managers with a better assessment of ongoing and past lake functioning.

Implications of environmental conditions on water quality issues are studied using paleoecological techniques which focus on assessment of biological indicators in the sediments to estimate climate and nutrient conditions (Saros et al., 2012). Sedimentary records provide important information regarding the functioning, climate, and biological history of a lake (Carey and Rydin, 2011, Saros et al., 2012). Chemical analysis of the sediments reveals past nutrient levels and trophic status (Carey and Rydin, 2011). Studies produced by the Global Lake Ecological Observation Network (GLEON) and other monitoring networks, use monitoring programs to assess lake conditions, such as trophic status in relation to total organic carbon (Dunalski, 2011). Ongoing monitoring programs establish baselines of lake functioning and water quality as well as detecting human influences on lake ecosystems (Queimaliños et al., 2012, Williamson et al., 2009).

Changing climate, linked to increased anthropogenic emissions of greenhouse gases, is expected to have significant impacts on general functioning of lakes whose ecosystems are affected by climate-driven processes such as temperature fluctuations, precipitation, solar radiation, and wind patterns (Battarbee, 2000, Williamson et al., 2009). Changes to these processes influence lake function, particularly through changes in water-column stratification with significant impacts on whole-lake nutrient and dissolved oxygen distribution (Battarbee, 2000). The ability to assess effects of climate change on lake ecosystems revolves around paleolimnological analyses of sediment cores and their properties (Saros et al., 2012, Williamson et al., 2009). For example, sediment core studies show that increased air temperature, a factor greatly associated with ongoing climate change, has a strong positive relationship with lake pH and ice extent all over the world (Koinig et al., 1997).

In tandem with 20th century surface temperature increases, water temperatures have increased in lake ecosystems and this trend is likely to continue with the additional warming predicted by climate models, (Saros et al., 2012). The effects of increased temperatures include biological responses, such as greater biological activity with associated increased demand for oxygen and other nutrients, and physical responses, such as altered thermal structure and water-column stratification (Saros et al., 2012). Solar ultraviolet (UV) radiation is expected to increase in future climate

scenarios, affecting both light penetration and biological activity in lakes (Häder et al., 2007). Increased UV radiation will have greater impacts on lakes with lower dissolved organic carbon (DOC) concentrations that help shade organisms from radiation (Rose et al., 2009).

Regional Water Quality Issues

Lakes play a vital role in the economy and well-being of central NH. They serve as important reservoirs of drinking water supplies, supply vital natural resources for recreation and tourism, and provide significant tax revenue local municipalities (Shapiro and Kroll, 2003). Total sales generated by surface water recreation and drinking supplies account for \$1.1-1.5 billion annually; water recreation related-activities produce 9,000-15,000 jobs and \$320-340 million in household income for the state of New Hampshire (Shapiro and Kroll, 2003). These lake resources are threatened by ongoing issues which include climate change, decreased water quality, and invasive species (Gibbs et al., 2002, Halstead et al., 2003, Williamson et al., 2009).

Changing climate impacts are of great concern in NH and throughout New England. Monitoring of temperature in central NH over 150 years has shown significant increases (Hamburg and Cogbill, 1988). Mean annual and summer temperatures have increased by 1.7°C and 2.2°C respectively over the period. Historical records of ice-out dates on northern New England lakes (1850-2000) show a decrease in ice coverage over that period (Hodgkins et al., 2002). During that same period, ice-out occurs on average 9 days earlier at the end of the record. This trend was strongly correlated with increased regional late-spring (April-May) air temperatures. Predictions of future temperature trends in New England and the Northeast with continued greenhouse gas emissions suggest year-round temperature increases (Griffiths and Bradley, 2007, Huntington et al., 2009, Moore et al., 1997). Seasonal temperature increases strongest in the winter. In addition to increased temperatures, regional predictions show increased seasonal precipitation, but decreased snow coverage (Huntington et al., 2004).

Decreased water quality has also become a major issue in New Hampshire lakes. Eutrophication due to high nutrient levels is the primary cause of decreased water quality mostly due to increased nonpoint source pollution (Gibbs et al., 2002). Eutrophication results in increased algal community blooms leading to decreased aesthetic and recreational resources for the lake (Nordstrom, 2007). Reduced water quality, particularly in clarity, are expected to have significant negative impacts on tourism and recreation. Studies show that loss of water clarity leads to lower lakefront property values and sales in New Hampshire and Maine (Gibbs et al., 2002, Michael et al., 1996). Ongoing monitoring programs, such as the NH Lay Lakes Monitoring Program (LLMP) and the NH Volunteer Lake Assessment Program (VLAP), assess lake water quality during the ice free period, generally May-September (NH Department of Environmental Services 2014, NH LLMP).

Determining the effects of climate and land-use on water quality is still a major issue that needs to be resolved. Research in lowland, temperate lakes is critical in

understanding how these issues affect areas with vast water resources and a heavy reliance on lakes for drinking water, recreation, and habitat. New Hampshire is an ideal study location for this type of project for several reasons. Firstly, NH has numerous lakes in close proximity to each other that can be used in comparative studies. Secondly, many of these lakes have histories of land use impacts and are today experiencing increasing human populations in their watersheds, with a staggering increase in shoreline development. Finally, the climate of New England has changed in the 20th century and these changes have been observed to affect the region's hydrology.

This study builds on these concepts utilizing sediment analysis and monitoring programs to assess climate and water quality trends. I studied two, central New Hampshire temperate, lowland lakes located in different watersheds to assess climate influences on water quality and their concordance with research hypotheses. Similar trends in water quality changes, recorded in the water-column and sediments of both lakes, reflect regional-scale climate-forcing rather than merely local, land-use influences. In the three centuries following European settlement, water quality issues in NH have been dominated by localized land-clearances and logging. In the 20th century, land-use changes include the waning impacts of prior logging and land-clearing, with widespread re-establishment of young forests and the waxing influence of rapid, anthropogenically-forced climate change.

This project targets a critical question for lake managers: which has more influence on current water quality, prior land use or ongoing climate change? Separating out the land use influences from climate on the water quality is critical in determining the impacts on water quality. Linking these two phenomena to water quality provides managers a better outlook on past conditions within the lakes and can guide future management decisions. This is especially important when considering the impacts of projected changes within their watersheds in light of a changing climate and increased anthropogenic land use shifts.

Broader Impacts

This project provides a baseline of lake functioning and better understanding of the relationship between climate and water quality in New Hampshire, in particular, and in lowland boreal forest regions of New England, in general. The temperature and water quality analysis provide an assessment of current lake conditions and shared with lake management and conservationists. This work also provides baselines for future studies, including ongoing sediment flux analyses in both watersheds. By further establishing correlations between climate and water quality issues, this study helps in understanding how water quality in New Hampshire lakes are impacted by 20th century climate change. Relationships found in ongoing monitoring and sediment analysis predict future impacts on lake ecosystems from climate change.

Both lakes are important centers for tourism, yet little information is available on the general conditions and functioning of these lakes. Climate and water quality issues threaten the functioning and vitality of these lakes and the economies based around the tourism and recreation industries in the lake regions. This study connects paleolimnological techniques with ongoing water quality and climate monitoring.

Most studies of climate and water quality focus on either paleolimnological or monitoring techniques, but combining the two strategies provides a better assessment of long-term climate and water quality trends. Established relationships between climate conditions and water quality with combined techniques helps in understanding future waters quality implications from changing climate conditions. Limited research on lake sediments has been conducted in New England and New Hampshire, in particular. This study addresses gaps in paleolimnological research in the region and provide more information on the sediment records in both lakes.

By working with community groups, this project builds stronger connections between Plymouth State University and the community. My main partners for this project, the Green Mountain Conservation Group (GMCG) and Squam Lakes Association (SLA), important leaders for sustainable management and conservation of these lakes and their surrounding watersheds. Both the GMCG and SLA coordinate water quality monitoring and conservation efforts in their respective lakes. Our partnerships helped me reach a larger audience of people interested in lake conservation.

**Distinguishing between land use and climate effects on water quality
in northern New England lakes**

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Abstract

Lakes are an important community resource and ecological system. As such, water quality within these systems is important to both humans and wildlife, however, quality degradation is becoming more prominent due to human influences. Assessing past water quality and how it was affected by natural and manmade influences, provides managers a means of determining future potential impacts from human activities and changing climate scenarios. In this study, I compared two lakes in central NH, with similar climate and land use histories, to determine how water quality within these systems are impacted by land use changes and climate events. I find multiple proxies that indicate both land use and climate impact the quality of the two lake systems with two interesting caveats. The first is that land use changes make watersheds more susceptible to extreme precipitation events, such as hurricanes, which leads to increased water quality degradation. The second is that the lake size to watershed area ratio determines the extent of this impact. In our study the lake with the greater ratio is more prone to high erosion events and dramatic declines in water quality due to the combined impacts of land use and climate.

Introduction

Water quality is currently one of the most important issues in management of surface waters. Of all surface bodies of water, lake systems are particularly vulnerable to impacts from their surrounding environment. Lakes are sentinels for change in their watersheds, with high residence times that take longer to recover from quality declines (Schindler, 2009). Lake water quality decline can be attributed to a number of factors including: nutrient pollution from non-point sources, surrounding watershed land use, tributary input, and changing climate. In most regions of the U.S. land use has changed significantly within the past two hundred years, historically with large scale land clearances for logging and agriculture, and in recent years, with a move towards a more spread out, large human population (Thompson et al., 2013). During this same period, most regions of the U.S. experienced changing climate trends, particularly in temperature and precipitation (Griffiths and Bradley, 2007). These combined impacts are likely to have a great impact on surface water degradation.

For lakes situated at low elevations, runoff from the surrounding uplands carries with it materials representative of the surrounding watershed and deposits from the airshed (Schindler, 2009). These are deposited in the lakes and are subsequently focused in thick accumulations in the deepest basins. Sediment cores of these deep basins provide continuous records, over historical timelines, of environmental conditions within the lake and its watershed (Smol, 2010). Sedimentary records provide important information regarding the functioning, climate, and biological history of a lake (Carey and Rydin, 2011, Saros et al., 2012). Chemical analysis of the sediments reveals past nutrient levels and trophic status (Carey and Rydin, 2011). Biological indicators, such as diatoms, are a proxy of past lake conditions and can be used to infer water quality conditions at the time of their deposition (Battarbee, 2001; Saros et al. 2012).

Shifts in land use and climate are observed through physical, chemical, and biological proxies within lake sediments including shifts in dominant grain size,

increases in erosion-related nutrients, and changing community compositions (Julià et al., 2007; Hausman et al., 2002; Smol and Cumming, 2000; Smol, 2010; Watchorn et al., 2008). In this study, I combine multiple proxies to assess changes in watershed land use and climate observed in two northern New England lakes. Changes in particle size, organic composition, geochemistry, and diatom communities within the sediments, provide comprehensive records of water quality changes within each lake. I compare these with local land use and meteorological records to assess dominant mechanisms for change. The primary hypothesis is that anthropogenic land use changes makes watersheds more susceptible to extreme storm events resulting in relative declines in water quality. A secondary hypothesis is that the influence of this land use change is stronger in lakes with a relatively small watershed as reflected by the watershed to lake area ratio.

Site Description

European settlement of the region around Squam and Ossipee lakes, located in eastern central New Hampshire south of the White Mountains (Fig 1), began in the 1760s, with most towns established before the 19th century (Carley, 2004). Historically, agriculture and timber harvesting were the predominant industries within these watersheds, but both industries have declined dramatically. Agriculture, especially sheep farming, dominated regional land use throughout the early to mid-1800s. Significant farm abandonment after the U.S. Civil War, as more farmland became available in the western U.S. (Donahue, 2007; Thompson et al., 2013), left timber harvesting as the primary land use industry in the region. This era lasted until the passage of the Weeks Act in 1911, which initiated a period of increased protection for NH's forests and the establishment of the White Mountains National Forest (Lewis et al., 2002). These restrictions, and migration of population into more urban areas, resulted in regional forestation over the last century, primarily of mixed deciduous and coniferous tree stands (Thompson et al., 2013). Currently, tourism is the region's dominant industry. In New England, particularly New Hampshire, lakes are an important resource for local communities serving as vital habitat for local wildlife, reservoirs for drinking water and tourism. New Hampshire's central lakes draw thousands of visitors each summer, prompting greater shoreline development. Lakefront properties are a major source of revenue for local communities.

Squam Lake (N 43.77-43°, W 71.58-48°) has a maximum depth of 30 m and a surface area of 2,737 ha (SLA, 2013; Fig 2). The watershed to lake area ratio (WA:LA) for Squam is 6.5. The deepest basin, known as Deep Haven, is located in the northwest corner of the lake. Squam and Little Squam Lake have 32 contributing tributaries with just one outlet (Schloss, 1998), with a 5 year average residence time (SLA 2013). Squam's shoreline is extensive and complex, with numerous coves and islands holding a combination of year-round and seasonal homes. Its watershed (17,166 ha) is also predominately forested (86%), with steep slopes that include the Squam Mountain Range. Squam's watershed has also experienced increased conservation activity with 24% of the watershed under conservation easements (SLA, 2013). Squam's water column is steeply stratified in summer and winter (dimictic) and ice covered in winter (usually between December-April). Water quality testing shows that the lake is well-oxygenated (5-14 mg/L), oligotrophic (TP < 5 ppb), and has high

water clarity (secchi depth: 4.3-7.2 m). Other parameters shows that Squam has a neutral pH (6.1-7.3), low alkalinity (2-8 mg CaCO₃/L), low specific conductance (23-60 µS/cm) and low turbidity (<1 NTU).

Ossipee Lake's (N 43.82-77°, W 71.16-11°) maximum depth is 18.5 m and its surface area is 1259 ha (NHDES 2013, Fig 3). The WA:LA for Ossipee is 66.7. Ossipee has four inlets including the Bearcamp, Lovell, West Branch, and Pine Rivers and one outlet, the Ossipee River which feeds into the Saco River in Maine. Ossipee's lake volume of 108,421,500 m³ has an approximate residence time of 0.22/yr (Ossipee Watershed Coalition, 2007). The deepest basin is in the southern portion of the lake. The lake is dam controlled with an annual drawdown of several meters each fall, for flood mitigation. Ossipee has been dammed continuously since the 1860s with several dam replacements (NHDES, 2011). The dam at the Ossipee River outlet is maintained by the NH Department of Environmental Services Dam Bureau which maintains water levels at 407.25 ft elevation during the summer and 404 ft during the late fall and winter. Summer water levels can reach as high as 410 ft. Ossipee is also dimictic and ice-covered in winter (December-April). Water quality testing shows that the lake is well-oxygenated (1-12 mg/L), oligotrophic (TP < 5 ppb), and high water clarity (secchi depth: 1-7 m). Other parameters shows that Ossipee also has a neutral pH (5.7-7), low alkalinity (1-8 mg CaCO₃/L), low specific conductance (17-70 µS/cm) with higher turbidity (<7 NTU).

The Ossipee Lake watershed (84,820 ha) is 82.2% forest, 4.9% wetlands, 3.9% development, and 1.4% agriculture (Fry et al. 2011). Thanks to the Ossipee Range, 13% of the watershed has slope gradients greater than 25% (Ossipee NH, 2006). Ossipee's shoreline is highly populated with a mix of seasonal and year-round homes. There are a few conserved areas in this watershed including the Ossipee Wetland Natural Area and Ossipee Pine Barrens.

Methods

Sediment coring

Cores from lake depo-centers provide continuous records of watershed changes through analysis of changes in the physical, chemical and biological character of the lake deposits (Last and Smol, 2002). To this end, we use multiple surface sediment cores from Squam and Ossipee Lakes, collected with Uwitec® gravity corer's 6 x 60 cm core tubes and 7 kg added weight in 2013, 2014 and 2015. The cores are from the deepest basins of each lake, approximately 30 m depth in Squam L. (Table 1) and 18 m in Ossipee L (Table 1). The three cores from Squam L. range in length from 31-34 cm while the 4 cores from Ossipee are 34-57 cm long. Sub-samples for each core are contiguous and at 1 cm intervals.

Sediment chronology

We establish core chronologies using ²¹⁰Pb concentrations in one core from each lake, analyzed by the St. Croix Watershed Research Station (St. Croix, MN) using an EG&G Nuclear alpha spectrometry system, polonium distillation, and ²⁰⁹Po and ²¹⁰Pb standards. Minimum core top ages are February 2014 for Squam Lake and

March 2015 for Ossipee Lake; analyses dates are June 2014 and April 2015, respectively. The dated cores are also analyzed for carbon content and magnetic susceptibility so these data series can be visually correlated to other, undated, cores within the same basin. Apparent intervals of change and transient events in each dated core provide age-scales to which the other cores can be aligned, a common technique colloquially known as wiggle-matching (i.e. Hoek and Bohncke, 2001; Schwander et al., 2000).

Sediment physical and chemical analyses

Sample treatments include freeze-drying in vacuum flasks on a Virtis Bench-top 2K, at -60°C and 10-20 mTorr, until dry, generally at least 72 hours. Water content for each sample is determined from sample weights before and after freeze-drying. Dried samples were riffled into subsamples for physical and chemical analyses, to ensure that subsamples are representative of the whole and are effective replicates. Organic matter content as loss on ignition (LOI) is measured by weight loss after ashing at 550°C for 2 hours (Dean 1974; Heiri et al. 2001). The organic content of sediments provides an indication of net productivity within the lake and its watershed.

Magnetic susceptibility is a measure of the concentration of magnetizable materials in a sample (Gale and Hoare, 1991). High magnetic susceptibility values often occur with watershed erosion events, corresponding to increases in influx of unweathered, terrestrial material and, often, to changes in climate hydrological processes (Oldfield, 2013; Thompson and Oldfield, 1986). Magnetic susceptibility and LOI typically have an inverse relationship because organic material has very low susceptibility. I use a MS3 Bartington meter and MS2B dual frequency sensor for magnetic susceptibility (MS) measurements on sediments packed into 3.2 cm^3 polystyrene cubes, with three replicate measurements, normalized by sample mass. Calculated values include mass magnetic (χ_{ms}) and frequency dependent magnetic susceptibility (FDMS).

Sediment geochemistry analyses provide chemical compositions of deposited materials. Changes in geochemistry can indicate changes in the types of materials deposited within the deep basin or changes in the conditions that keep ions bound to the particles, such redox state, lake bottom temperatures and pH (Engstrom and Wright, 1984; Dean 1993; Hamilton-Taylor and Davidson, 1995). Inductively coupled plasma optical emission spectroscopy (ICP-OES) geochemistry results come from the 2013-1 core at Squam Lake and the 2014-2 and 2014-3 cores at Ossipee L., analyzed by Activation Laboratories (Ancaster, ON) on an Agilent 755 using near-total digestion methods. Cores were chosen for analysis due to compatibility with dated materials from each lake. For comparison purposes, values were standardized by subtracting the mean for each element and dividing by the standard deviation ($z = (x - \mu)/\sigma$).

Particle-size reflects the source, travel distance and energy of sedimentary deposits (Friedman and Sanders, 1978). Most lake particles range in size between 0.5-30 μm , with deviation from this size indicating influx of coarse sediments from the streams and watershed (Gale and Hoare, 1991). Analysis of particle size samples (0.5 g) on a Horiba LA-920 laser scattering particle size analyzer followed standard protocols, with digestion in 30% hot H_2O_2 ($70-90^{\circ}\text{C}$) for 3-6 hours and DI water rinses

(Gale and Hoare, 1991; Schumacher, 2002; Vaasma, 2008). Resuspension in a 5% Calgon solution and ultra-sonication just prior to measurement breaks up particle clumps.

Diatom analyses offer insight into past water and watershed conditions based on shifts in community composition (Battarbee et al., 2001). Diatom sample preparation also include digestion, in 10% HCl and 20% H₂O₂, until reactions are complete (1-2 weeks per digestion) with 3-7 rinses in DI water between treatments (Battarbee et al., 2001; Ruhland et al., 1999). A small portion of the sample is dried on a coverslip and fixed to a microscope slide with Naphrax® mounting solution. Specimens are identified at 100x magnification, with oil immersion. I identified 300 specimens per sample, to the species level when possible, from cores Squam 2014-3 and Ossipee 2014-3. In Squam, only the upper 15 cm have been analyzed, extending to ca AD 1945. In the Ossipee core, diatoms have been analyzed for the entire core, extending to ca. AD1840, determined by comparing the undated 2014-3 LOI curve with the dated LOI curve from 2015-1 (Fig X). Each sample is spiked with a known concentration of 5µm plastic microspheres to enable calculation of actual diatom concentration. Concentrations are calculated by multiplying the number of diatoms counted (>300) by the concentration of microspheres introduced to the sample and then dividing both by the number of microspheres counted (Battarbee and Kneen, 1980). These, in turn are statistically analyzed for community variance and association with environmental parameters using species relationships (Birks et al., 2012), with training sets established by Joynt and Wolfe (2001).

Water Monitoring

Water samples were collected to provide an assessment of current lake conditions and for diatom-inferred water quality parameters such as temperature, pH, and total phosphorus. Samples for water quality analyses come from the deep basin location in each lake, proximal to the core sites and also to long-term monitoring sites from February 2014 - April 2015. Long-term data for Squam is available by contacting the SLA and NH LLMP while records for Ossipee are available from the NH DES website (<http://des.nh.gov/onestop/>). *In-situ* data include water clarity by secchi disk, except during ice-cover periods, and depth profiles by YSI ProfessionalPlus temperature and DO sonde with a 20 m cable. Using a Kemmerer-style water sampler, we collected from the epilimnion (1 m depth), metalimnion (variable depths depending on season) and hypolimnion (within 2 m of lake bottom) to assess the influence of thermal stratification on various parameters. Additional measurements on these discrete water samples include pH (Orion Star A214 pH meter), alkalinity, turbidity, total phosphorus (LaChat QC8500), and major cations and anions, at Plymouth State University's water analysis laboratory.

Land Use and Meteorological Data

Land use data compilations from multiple sources provide the history of changes in watersheds of the study lakes. NH State and township population numbers are from the U.S. Census (1790-2010) and the NH Office of Energy and Planning. I extracted the population values for all towns within each watershed. Sheep

populations within the state and county (when available) are based on the U.S. and the New Hampshire Agricultural Census (1840-2012).

Meteorological records are compiled from the NOAA National Climate Data Center (NCDC) and Plymouth State University from stations in Plymouth NH from 1887-2014. While there were some data records available at stations within each lake's watersheds, the longest records available for the region were based in Plymouth NH. Plymouth is within the Squam watershed, but is approximately 59.5 kilometers from the Ossipee watershed. This data supplements water temperature data inferred from diatom communities.

Statistical Analyses

To test the primary hypothesis, statistical analyses were used to find the relation between proxies closely connected with land use and water quality. To test the secondary hypothesis, both qualitative and quantitative comparisons were made between lake proxies. Variation between select physical sedimentology, geochemical, and biological proxies within samples was analyzed using correspondence analysis (CA) and principal components analysis (PCA). CA and PCA was conducted using the C2 software program (Juggins, 2014). T-tests were conducted to compare proxy results between lakes. Hierarchical cluster analysis was performed for diatom species using the open-source software R.

Results

Land Use and Meteorological Records

The Squam and Ossipee watersheds both have a history of changing dominant land use and shifts in populations. There is an obvious correlation between a human population boom during the 1800-1865 period and the sheep population at that time (Fig 4). This correlates with other available records which attribute sheep farming to one of the most important economic factors to population growth during that period. Land held in farms also varied significantly over time, with a large land area being used for farming in the state between 1840-1900 (Fig 5). To link land use effects with meteorological events, the focus is on comparing extreme events, hurricanes and tropical storms, with sediment proxies. Available records for these events date back to the 17th century (Fig 6).

²¹⁰Pb Dating

²¹⁰Pb supported activity in Squam Lake core SQ2014-2, collected in 2014, reaches minimum background rates at 1.00 ± 0.075 pCi/g, 31 cm below the sediment surface (Fig 7). The core top concentration of ²¹⁰Pb is 67.36 pCi/g, with a near exponential age and depth relationship and an annual flux of 1.07 pCi/cm²/year. The constant flux: constant sedimentation and constant rate of supply models are in close agreement. The oldest reliable ²¹⁰Pb date for this core is 1815 ± 22 A.D. Sediment accumulation in the core has been continuous with an average rate of approximately 0.19 cm/yr since 1900 and, prior to that, the average rate is 0.01 cm/yr. Dry mass accumulation rates are above average for the entire interval from 1929-1978. A distinct minima in accumulation occurs at 1999 ± 1.8 yrs.

In Ossipee Lake, core 2015-1, supported ^{210}Pb activity is markedly high at 3.27 ± 0.05 pCi/g. The concentration of ^{210}Pb is 14.55 pCi/g at the core surface, collected in 2015. Excess concentration is measureable to 37 cm below the sediment surface (Fig 8). These concentrations vary over time with a monotonic downcore decrease with changes in slope and an annual flux of 0.74 pCi/cm²/year. The oldest reliable date for this core is 1827 ± 47 A.D. Sediment accumulation in the core has been continuous ranging from 0.08-0.13 cm/yr prior to 1990 and an average rate of approximately 0.26 cm/year after 1990. Of special note are maxima in sediment accumulation rates from 1936-1938 (± 2.0 yrs), and 1947-1951 (± 2.8 yrs). Rates return to near average values after each maximum. A lesser maximum accumulation occurs near the core top, around 2012.

Sediment Physical and Geochemical Characteristics

The Squam 2014-1 core, at 34 cm the longest of those collected in 2014 (extending to AD 1801 ± 12.8 years), is very similar to the three other surface cores from this basin, comprised of very dark-colored gyttja throughout, with no visually distinct layers. Each of the Squam cores is progressively enriched in both organic content and magnetically susceptible materials towards the core tops, with marked increases above 20 cm (AD 1898 ± 2.5 years), (Fig 9). Many of the geochemistry variables also show significant differences above and below 20 cm, as well as an earlier and more transient event between 30-32 cm (AD $1816-1832 \pm 12.8$ years; Fig 10).

The Ossipee 2015-1 core (57 cm long), the longest of four cores, is comprised of organic-rich gyttja with a range in organic content of 12.8-20% and $9.1-42.3$ μm mean particle size (Fig 11). At the depth beyond which the other three cores failed to penetrate, ca. 34 cm (AD 1841 ± 30 years), there is a marked transition in 2015-1 (Fig 12). At this depth, core color transitions from a lighter tan-brown below, to a dark brown above, and organic content, magnetic susceptibility, and particle size undergo significant change.

Particle size in Squam Lake particle sizes range from 0.23 to 300.5 microns, with mean values in each sample ranging from 9.4 to 29.0 microns (Fig 13) and a distribution of clays, silts, fine sands, and medium sands in select samples (Fig 14). Two events stand out at 2 cm and 14 cm, corresponding to AD. 2010 ± 1.5 years and 1942 ± 1.7 years, respectively. In the earlier event, there is an increase in fine sands relative to clays. In the latter event, there is a modest increase in clays and sands. From 1816-1892, relatively high mean particle sizes reoccur in pulses which also relates to higher abundance of fine and medium sands.

Particle size in Ossipee Lake varies between 0.09-262 microns, with mean values ranging from 6.9 to 20 microns (Fig 15 and 16). Maximum standard deviations throughout the two cores analyzed are 8.0 and 9.1 microns, for OSS2014-3 and OSS2015-1, respectively. Transitions between grain sizes classifications were also assessed (Fig 17 and 18). There is a distinct zone of high particle size frequency in the deepest sediments (49-50 cm), corresponding to A.D. $(1724.9-1656.9 \pm 46.8)$ years). These transitions correlate with periods of higher abundance of fine and medium sands prior to European settlement.

Inorganic geochemistry values from both lakes undergo high magnitude changes downcore. Redox-sensitive elements, such as Fe, Mn, and Mo, increase near the core tops in both lakes, but otherwise do not seem to be associated with the larger scale changes apparent in the graphs. Box and whisker plots of the major elements show the variation in standardized elemental concentrations within the sediments (Figs 19 and 20). To assess the relationships between geochemistry and physical chemical characteristics, a PCA was conducted to look at trends and assess how land use related signals, particularly grain size, are correlated with water quality variables (Figs 21 and 22). PCA results from Squam showed an inverse relationship between particle size and other indicators of water quality. Particle size at this lake was not strongly linked to magnetics (FDMS), a proxy for erosion of terrestrial soil materials, which is an indication of another influence, *ie.* storm events, on altered material deposition in the lake. Ossipee PCA, however, showed the opposite relation with a combined effect of grain size and magnetics (FDMS) that had a similar influence with select geochemical properties and organic content.

Squam and Ossipee Lake both show strong influences of atmospheric depositions in the sediment geochemistry (Fig 23). In Squam, this is indicated by a gradual buildup of the concentration of Pb and Cd, starting about 19 cm (ca AD 1913 \pm 3.2 years), peaking around 9 cm (ca AD 1981 \pm 2.4 years). In Ossipee, there is a similar, gradual buildup in Pb and Cd concentrations, starting about 26 cm (ca AD 1927 \pm 2.6 years) and peaking around 12 cm (ca AD 1967 \pm 2.1 years). Given the time period of deposition, the reductions in these elements in recent years are likely the result of decreased industrial and automotive atmospheric emissions following the passage of the Clean Air Act. Lead, in particular, a primary component of gasoline, is heavily concentrated in soils and sediments around the world during the early to mid-20th century. Atmospheric concentrations decreased with the widespread introduction of unleaded gasoline in the 1970s (von Storch et al., 2003, Wu and Boyle, 1997). Squam Lake's geochemistry also shows another earlier event (Fig 24). This event is defined by a change in most elements around 1808 (\pm 6.4 years). A possibly related peak occurs in arsenic in 1816 (\pm 6.4 years). Mobilization of redox-sensitive elements can create minor leads and lags in sediment chemical species, and this effect has been documented in lake sediments with As (Smedley and Kinniburgh, 2003).

Diatoms

Both lakes show variation in diatom community composition over time with transitions between species over time. The diatoms are typical of those found in New England, especially deep, oligotrophic lakes (Ginn et al., 2007). The sediments of Squam Lake contain 29 genera and 82 species, most common in New Hampshire sediments. Of these genera there are 5 that are relatively abundant including centric and pennate diatoms: *Aulacoseira distans*, *Cyclotella comensis*, *C. bodanica*; *Discostella stelligera*, and *Tabellaria fenestrata*. Major community transitions occur between 1-2 cm (ca. AD 2012-2010), 8-9 cm (ca. AD 1985-1980), and 12-13 cm (ca. AD 1958-1963; Fig 25). Cluster analysis of all genera and abundant species shows strong correlations between communities (Fig 26). Correspondence analysis indicates that variance in certain samples are primarily associated with inorganic elements rather than diatom species (Fig 27).

Ossipee Lake sediments are relatively species rich with 160 species and 39 genera (Fig 28). This is almost twice the number of species as Squam. There are 9 relatively abundant (>5%) genera and 8 relatively abundant (>5%) species. Of those 8 species, 5 were the most abundant in Squam while the remaining 3 include *Discostella pseudostelligera*, *Tabellaria flocculosa*, and *Achnantheidium kriegei*. For statistical purposes *Discostella stelligera* and *D. pseudostelligera* were combined due to current debate about the distinction between these species. Major transitions in *Achnanthes* and *Tabellaria* concentrations occur after AD 1940 while an abrupt decline in *Achnantheidium kriegei* occurred after AD 1980. Cluster analysis of all genera and abundant species shows strong correlations between communities (Fig 29). Correspondence analysis of all genera with abundant species shows strong outliers in *Comensis bodanica*, *Aulacoseira bodanica*, and *Prestauronis spp.* that dominate the distribution of this dataset. Similar to Squam, correspondence analysis of this dataset is dominated by inorganic geochemistry with diatom diversity clustered towards the center (Fig 30a,b).

Lake-Lake Comparisons

Quantitative comparisons between lakes shows that there are significant differences in proxies. Focusing on Squam 2014-3 and Ossipee 2014-3 cores, there was a significant difference between organic content ($n=32,34$; $t=13.03$, $p<0.001$), low frequency magnetic susceptibility ($n=32,34$; $t=-7.56$, $p<0.001$), and grain sizes ($n=32,34$; $t=2.04$, $p=0.049$). Qualitative comparisons between PCA, CA, and hierarchical clustering analyses as well as the frequency of peak grain size increases show that Squam Lake is more responsive to storm events than Ossipee Lake.

Discussion

Ossipee and Squam Lakes exhibit different transitions in their physical, chemical and biological characteristics that are correlated to land use change and climatic events. Similarities in proxy responses to external influences indicate regional trends while lake differences are watershed specific responses. Our first hypothesis was that historical land use leaves a watershed more susceptible to extreme events, such as tropical storms and hurricanes. This susceptibility is reflected by correlating changes in our proxy data with regional meteorological and land use data. Our second hypothesis is that this susceptibility has an inverse relationship with watershed area to lake area ratio.

Lakes with a smaller WA:LA ratio have a shorter residence time, flushing out excess nutrients that have the potential to degrade water quality (Lillie and Mason 1983). Other studies have found a strong influence of this ratio on water quality as it is an indication of the effectiveness of the lake to transport materials (Fraterrigo and Downing 2008, Shaffer et al. 1988). The capacity of the watershed to transport materials to the lake is highly influenced by its comparable size with the area of the lake. As such, lakes that have a high transport capacity are more responsive to processes outside of the lake, such as land use (Fraterrigo and Downing 2008). This impact how a lake responds to storm events, with larger lakes in smaller watersheds experiencing impacts of large events faster and at a higher magnitude than those with a higher WA:LA ratio. We found evidence for this in Squam Lake, which showed

more responsiveness to extreme events in its physical and geochemical proxies. Statistical analyses including t-tests, PCAs, and DCAs all showed different results between lakes on all proxies.

Particle size analyses in for both lakes shows higher increased frequencies of coarser mean grains sizes during a period of wide spread land clearances for agricultural use in their respective watersheds circa 1800-1900. Both lakes also have pulses of coarser grain sizes that correspond with extreme precipitation events. The relationship between sediment particle or grain sizes and erosion tend to be is a positively correlated. Multiple studies have found that increases in the average mean or median grain size are associated with greater intensity of precipitation levels and can be used as a proxy for large-scale climate events, *ie.* hurricanes or monsoons (Peng et al. 2005, Scileppi and Donnelly 2007). Earlier pulses (prior to 1860s) in coarser grains were likely contributed to greatly by land clearance that can be attributed to high soil disturbance and precipitation intensity. New England forests began to recover quickly after large-scale farm abandonment post-Civil War and stabilized by the late 1800s, but the hydrology of the region took longer to recover. Modern variability (post-1900) in grain sizes can be attributed to higher precipitation intensity rather than any large-scale soil disturbance. This relationship is more prevalent in the Squam watershed when compared to Ossipee, an indication of a more responsive watershed.

Organic content in Squam declines following this transition around 1900 from a period of high agricultural land use to a more reforested state. Organic content also sharply dropped following the installment of a dam in Ossipee Lake circa 1860s. This suggests that either lake or watershed productivity decreased or a combination of both. Decreased productivity can be used to infer a reduction in nutrient inputs to either the lake or its respective watershed (Meyers and Lallier-Vergés 1999), however, without isotopic and carbon-nitrogen ratios, the source remains undetermined. Also around 1900 when organic content declines, there are peaks in low and high frequency magnetic susceptibility in Squam. Increases in magnetic susceptibility is related to the introduction of new magnetizable material to the lake, such as inputs of eroded soils from the surrounding watershed. Studies have found magnetic susceptibility as a meaningful proxy for indicating an increase in eroded soil matter that can result in increased metals pollution (Schmidt et al. 2005). Further research into the specific sources or provenance of organic and magnetic materials to the lakes can provide useful information about the environment at the time of deposition (Meyers and Teranes 2001).

Inorganic geochemical analysis shows two distinctive, large-scale events, approximately dated at 1815 and 1920-1980. The earlier event is only distinguished in Squam Lake. These events occur during the same time period when the region had high populations combined with a predominantly agricultural land use. In addition to sedimentation eras of change associated with land use, several pulses of fine and medium sands deposited in the lakes can be correlated to regional big climate meteorological events, hurricanes and or tropical storms that made landfall in New England. An earlier event, seen only in the Squam samples, pertained is apparent to in

only a single pulse sample, but across multiple in elemental dated concentrations between 1806 and 1815.

This was a period of high agricultural land use, including sheep farming. In 1815, a hurricane that made landfall in NH and was a significant storm event in central NH (Boldt et al. 2010, Boose et al. 2001). Hurricanes events have been shown to result in create pulses of increased coarser grain sizes sediments and an influx of metals to the lake and can be reconstructed using lake sediments (Brandon et al. 2014). The 1815 hurricane has been shown to be a significant storm event whose projected trajectory included the central NH region (Boldt et al. 2010). This event was not observed in the Ossipee samples, but inorganic geochemistry analyses results were not conducted on samples for that same time period. As such, further analysis of Ossipee sediments could determine that if this is a regional rather than watershed specific event.

The later event, seen in both watersheds was is distinguished by a gradual increase and then subsequent decline in these metals elements between the 1920s and 1980s. Each element in the second event, which includes Pb, Cd, and Zn, are highly associated with industrial and commercial use and are emitted to the atmosphere. The decline of these elements post 1980 can be seen as reflection of either a decrease in emissions (likely due to the Clean Air Act of 1970) or a change in processes that bind these elements to sediment particles. This relationship between industrial activities and metals in lake sediments has been well documented (Graney et al. 1995, Renberg 1986, Renberg et al. 2001). Multiple studies have found that in lake sediment concentrations of certain heavy metals associated with human emissions has declined since the 1970s in lake sediments (Kamman and Engstrom 2002, Renberg et al. 2001, Tylmann 2004). Mahler et al. (2006) found that concentration of metals decreased between 46-3% between the 1970s-90s in urban lakes.

Differences in diatom communities are a strong indication of changing environmental conditions within the lake system. Variations in species richness (biodiversity) indicates shifts in nutrient availability and environment and can be used to infer water quality conditions. Jeppensen et al. (2000) reports strong correlations between total phosphorus (TP) levels in Danish lakes and diatom species richness. It is important to note that increased species dominance of a few species (*ie. Cyclotella*) is also associated with nutrient enrichment (*ie. Interlandi et al. 2003*). Historical events can also strongly influence modern diatom species compositions (Vyerman et al. 2007). However, several key diatoms like *Cyclotella* found in both lakes, are also associated with warmer temperature and associated nutrients. Several studies have found that *Cyclotella* is associated with phosphorus-rich conditions, but can remain dominant after phosphorus levels decline (Cumming et al. 2015, Kistenich et al. 2014). In this study, the higher species richness in Ossipee compared to Squam, suggests a combination of warming temperatures and nutrient enrichment. *Discostella stelligera*, a planktic species, has increased significantly in Ossipee Lake since the 1940s. This species is associated with higher nutrient content and is a sign of phosphorus enrichment (Saros et al. 2014).

While the use of diatom inferred temperature ranges remain controversial due to the conflicting influences of pH, habitat availability, and nutrient availability on diatom community composition (Anderson 2000, Battarbee 2000), diatoms remain an excellent indication of changing water quality conditions (Bigler and Hall 2003). Planktonic species, like *Aulacoseira distans* and *C. comensis*, can also be indicators of warmer water temperatures and ice-free conditions (Bigler and Hall 2003, Kistenich et al. 2014). Centric diatoms including *Cyclotella* and *Discostella* that were dominant in both lakes are considered indicators of warming climate conditions (Rühland et al. 2008).

Saros et al. (2012) study of diatoms in the western U.S. developed an index of inferred water mixing depth using three species found in both of the lakes of this study: *Cyclotella bodanica*, *C. comensis*, and *Discostella stelligera*. Although the interaction between nutrients and temperature are difficult to separate, their study showed that *C. bodanica* exhibited the strongest relationship between mixing depth and abundance while *C. comensis* and *D. stelligera* have greater dependency on nutrients. *C. bodanica* in Ossipee Lake has a peak period from 1880-1960 AD indicating that the relative mixing depth is deeper due to warmer temperatures during this period. It is during the decline of this species in the 1960s, that *C. comensis* abundance begins to increase which also has an association with deeper water mixing. The transition between these two species likely represents a shift in nutrients available in the lake that favored *C. comensis* post-1960. Also in Ossipee Lake there is evidence of shifts between benthic (*ie. Achnanthes*) versus planktonic (*ie. Comensis*) species over time with a decline in *Achnanthes* starting in the late 1930s. Populations skewed towards planktonic species indicates warming water temperatures (Rautio et al. 2000) which is consistent with warming air temperatures in the region over the 20th century.

It is apparent that greater land use disturbance in the earlier part of the record corresponds with a period of higher agricultural production and human populations within each watershed. This relationship resulted in a negative impact on overall water quality within the lakes. However, this relationship is more prevalent in the Squam watershed. Given that both watersheds had similar land use, climate, and human population patterns between them, the most plausible reason for this relationship is the size of each lake and its respective watershed. Lake size is greater in Squam, but Ossipee has a greater watershed area. As such, Squam has a WA:LA that is almost one tenth of Ossipee's. With Squam exhibiting more frequent and severe changes in the lake sediments and diatom communities, it is suggestive that the watershed to lake area ratio dominates a lakes ability to respond to land use and climatic influences. However, the condition (quality) of the watershed must also be considered when assessing past or current impacts of land use and climate on water quality.

These relationships show that both lakes are susceptible to the influence of climate events, particularly when land use in the watershed is heavily modified. While most of northern New England has returned to being predominately forested, there are still significant risks to the stability of land use in the region. With predictions of increasing human populations and associated increases in development and agriculture land usage these watersheds have the potential to be significantly impacted. Studies

have found strong linkages between human development and a host of negative environmental issues including the spread of invasive species, phosphorus pollution, and contaminated runoff (Gavier-Pizarro et al. 2010, Rhodes et al. 2001). These watersheds will be susceptible to changing climate and the projections of increased frequency of higher intensity storm events and overall increased precipitation in the region (Huntington 2006). The combination of changes in land use and climate impacts can have detrimental effects on the water quality and subsequent use of these lakes as resources for the local communities (Moore et al. 1997). As such, managers and decision makers need to plan for controlled development and land use in watersheds while recognizing that their systems are already impacted by historical land use legacies (Foster et al. 2003). Cooperative efforts between managers, government agencies, and the local community are needed to prevent further water quality degradation in our lakes and increase community resilience to climate change.

Further research into this issue needs to focus on how water quality is impacted by climatic events and how this is influenced by land usage. Extended, high frequency paleolimnological records of hurricane and other extreme storm events are needed to make stronger correlations between changing water quality and these events. While there has been extensive increase in our understanding of when hurricane events have struck the New England region (*ie.* Donnelly et al. 2001, Donnelly et al. 2015, Noren et al. 2002, Scileppi and Donnelly 2007), these records can be expanded. In addition to expanding our paleo records of hurricane events, greater emphasis is needed on assessing shifts in water quality pre-colonization to the present. The use of diatom-inferred water quality, geochemistry, and grain size analyses helps provide a more complete perspective on changes during that time period.

Acknowledgements

I would like to acknowledge all those who assisted in field collections and laboratory analyses. Financial support for this study came from Plymouth State University, Geological Society of America, Sigma Xi, and the International Phycological Society.

Tables

Table 1: Squam Lake Sediment Cores

Core Name	Collected	GPS coordinates	Water Depth (m)	Core length (cm)*	Number of Samples
Squam 2014-1	2/26/2014	43°46'45.9" N 71°8'19.9" W	29.6	36	34
Squam 2014-2	7/10/2014	43°46'49.3" N 71°8'25.8" W	31.5	34.5	31
Squam 2014-3	8/29/2014	43°46'49.3" N 71°8'25.8" W	30	36	32

*Core length includes core piston and cap

Table 2: Ossipee Lake Sediment Cores

Core Name	Collected	GPS coordinates	Water Depth (m)	Core length (cm)*	Number of Samples
Ossipee 2014-1	7/19/2014	43°46'45.9" N 71°8'19.9" W	17	46.5	34
Ossipee 2014-2	9/1/2014	43°46'49.3" N 71°8'25.8" W	18	39.4	36
Ossipee 2014-3	9/1/2014	43°46'49.3" N 71°8'25.8" W	18	38.1	34
Ossipee 2015-1	3/29/2015	43°46'46.1" N 71°8'19.5" W	14	62	57

*Core length includes core piston and cap

Figures

Figure 1: Overview of the study area location in central New Hampshire.

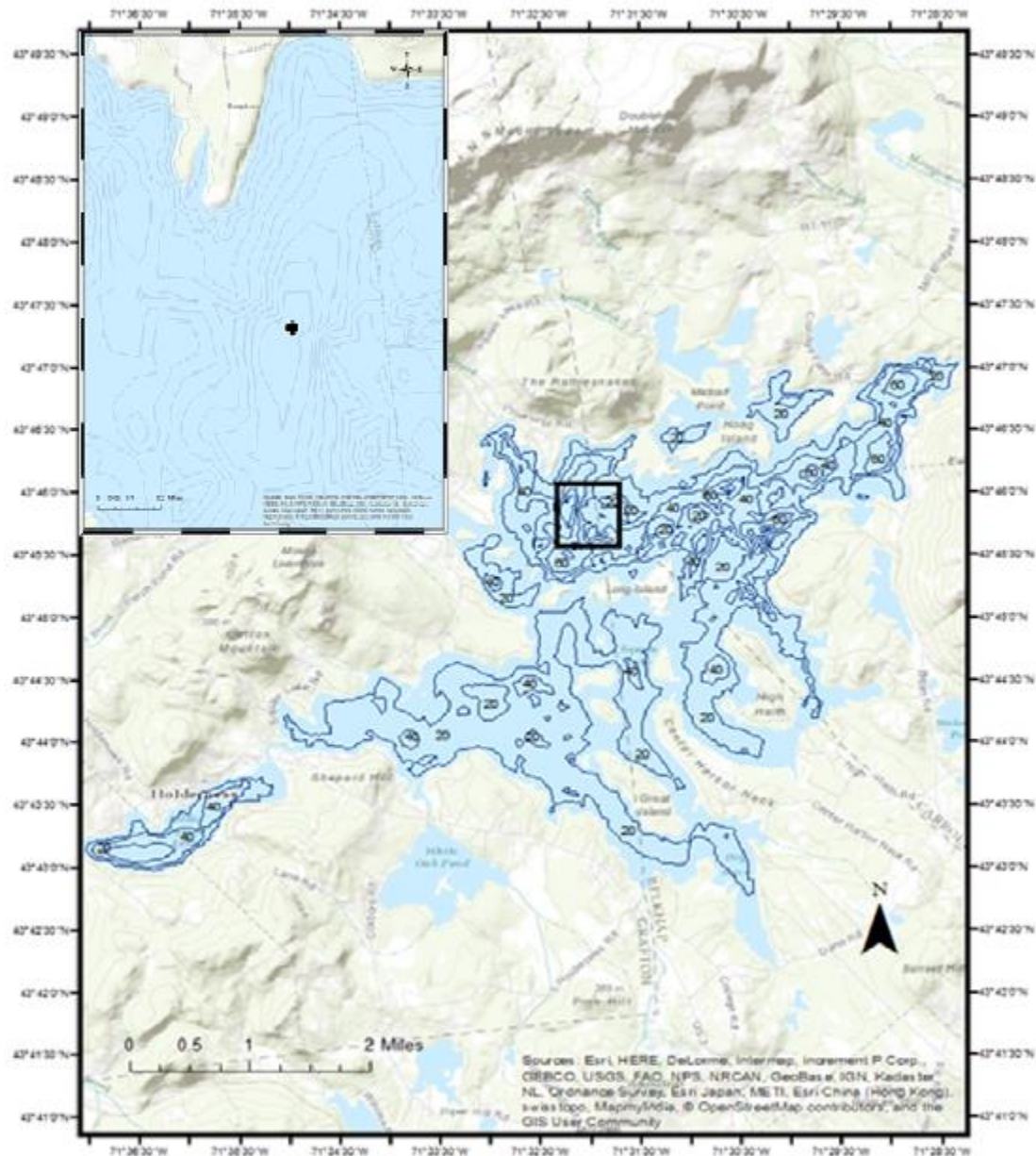


Figure 2: Squam Lake bathymetry. The monitoring and coring location in Deep Haven Deep, at 29 m the deepest region of the lake, is marked as by a black dot in the inset box. Bathymetry shape layers courtesy of NH Fish and Game Department. Each isoline depicts a 20 ft depth contour interval.

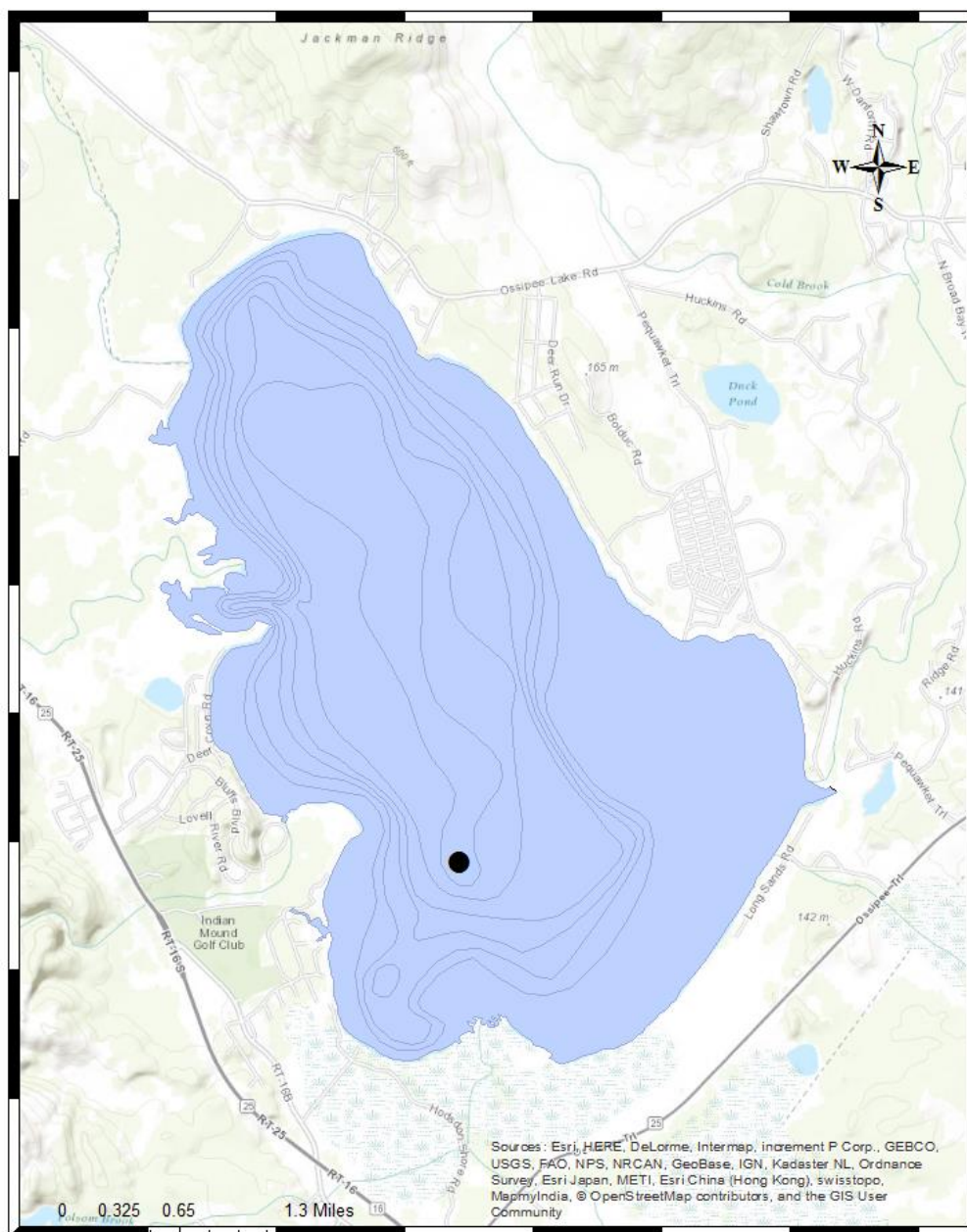


Figure 3: Ossipee Lake bathymetry and the location of the sediment core sites (black dot). Bathymetry shape layers courtesy of the NH Fish and Game Department.

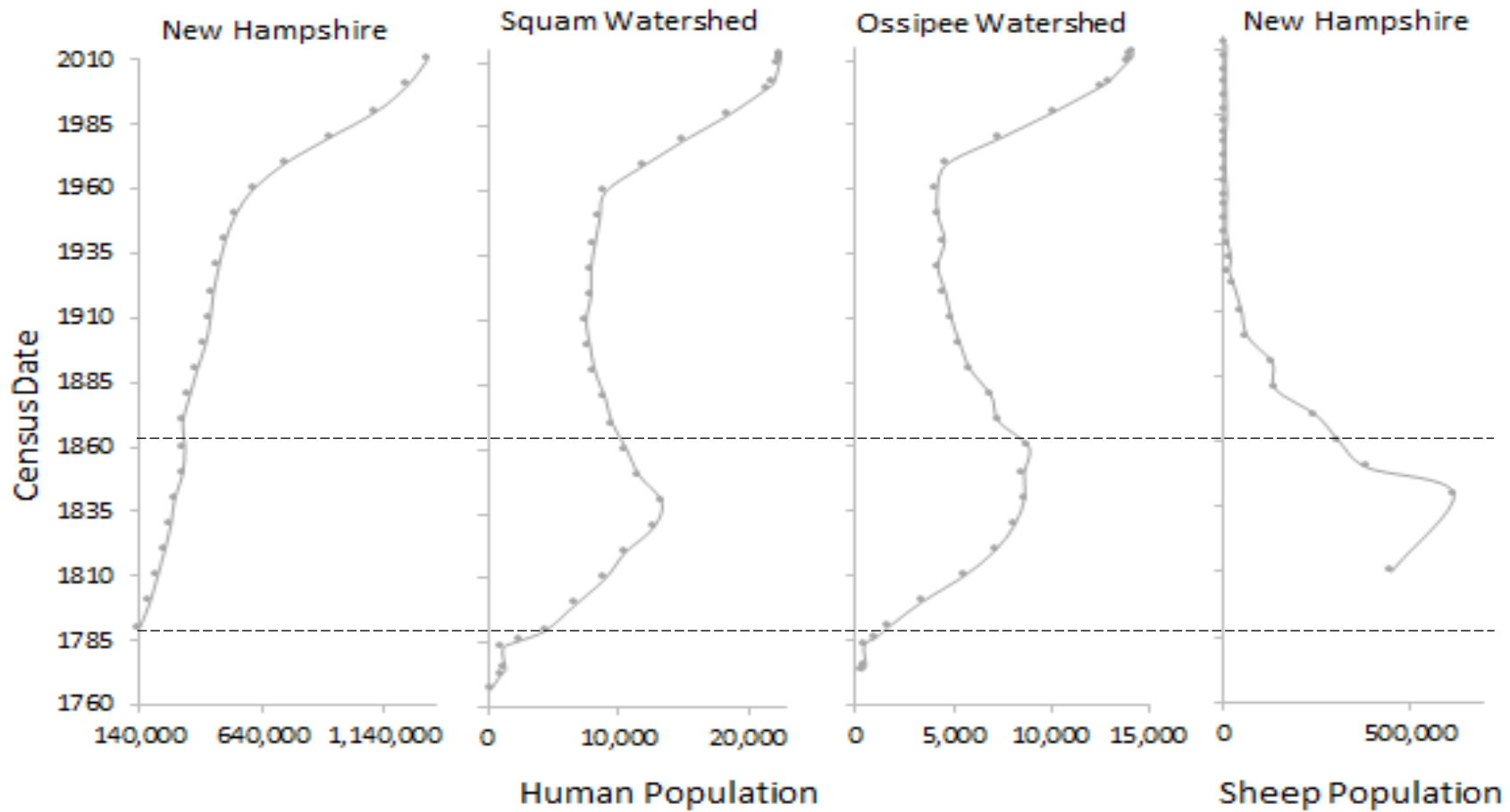


Figure 4: Overview of the human population in the state of NH 1790-2010 in comparison with the population of towns within the Ossipee Lake and Squam Lake watersheds 1763-2013. These populations are compared with the sheep population in the state of NH from 1810-2012.

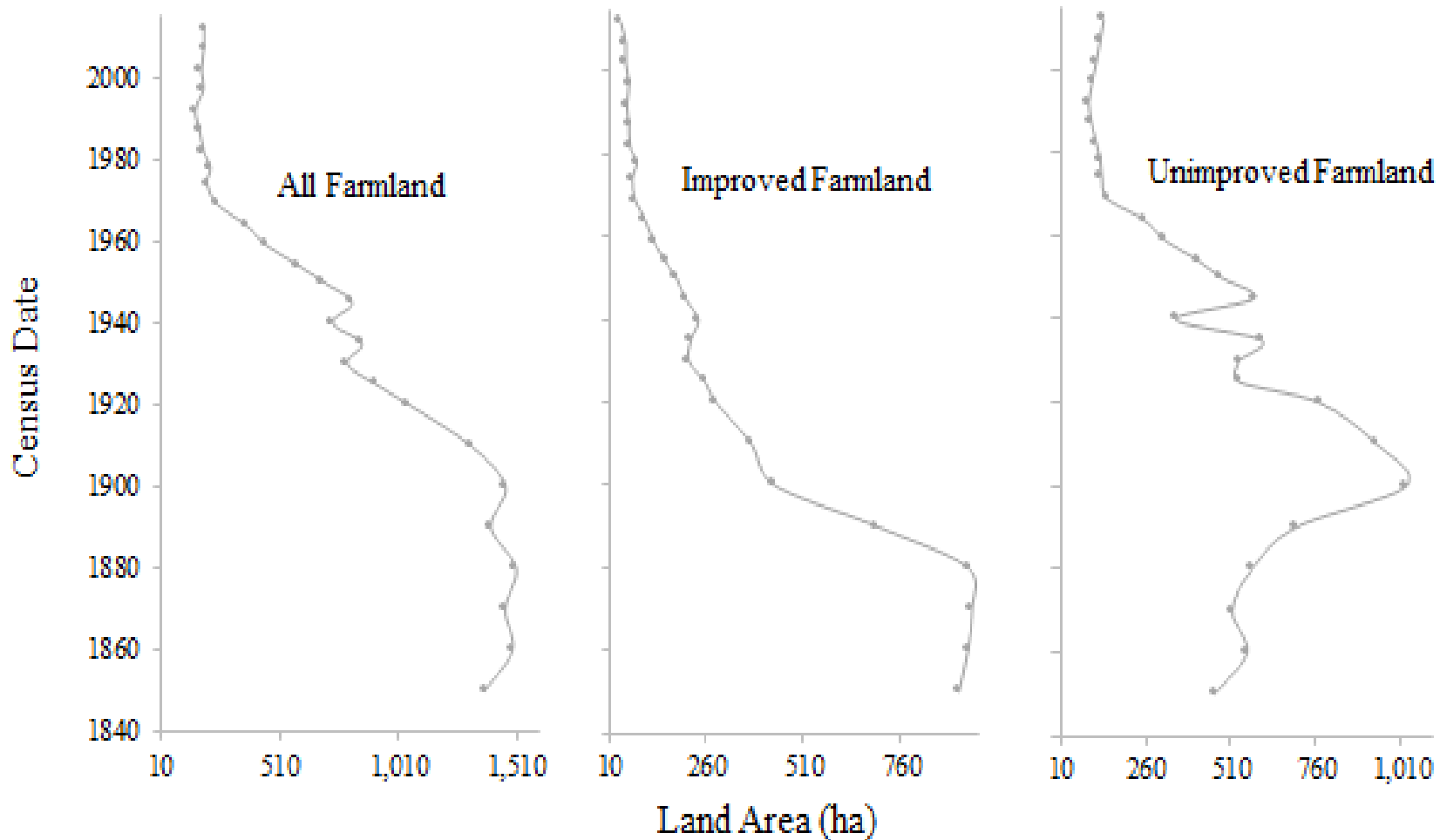


Figure 5: Changes in land area held in farms in the state of NH 1840-2012. This graph includes all farmland, improved or tilled cropland, and unimproved farmland which includes untilled pasture, graze land, and woodlots.

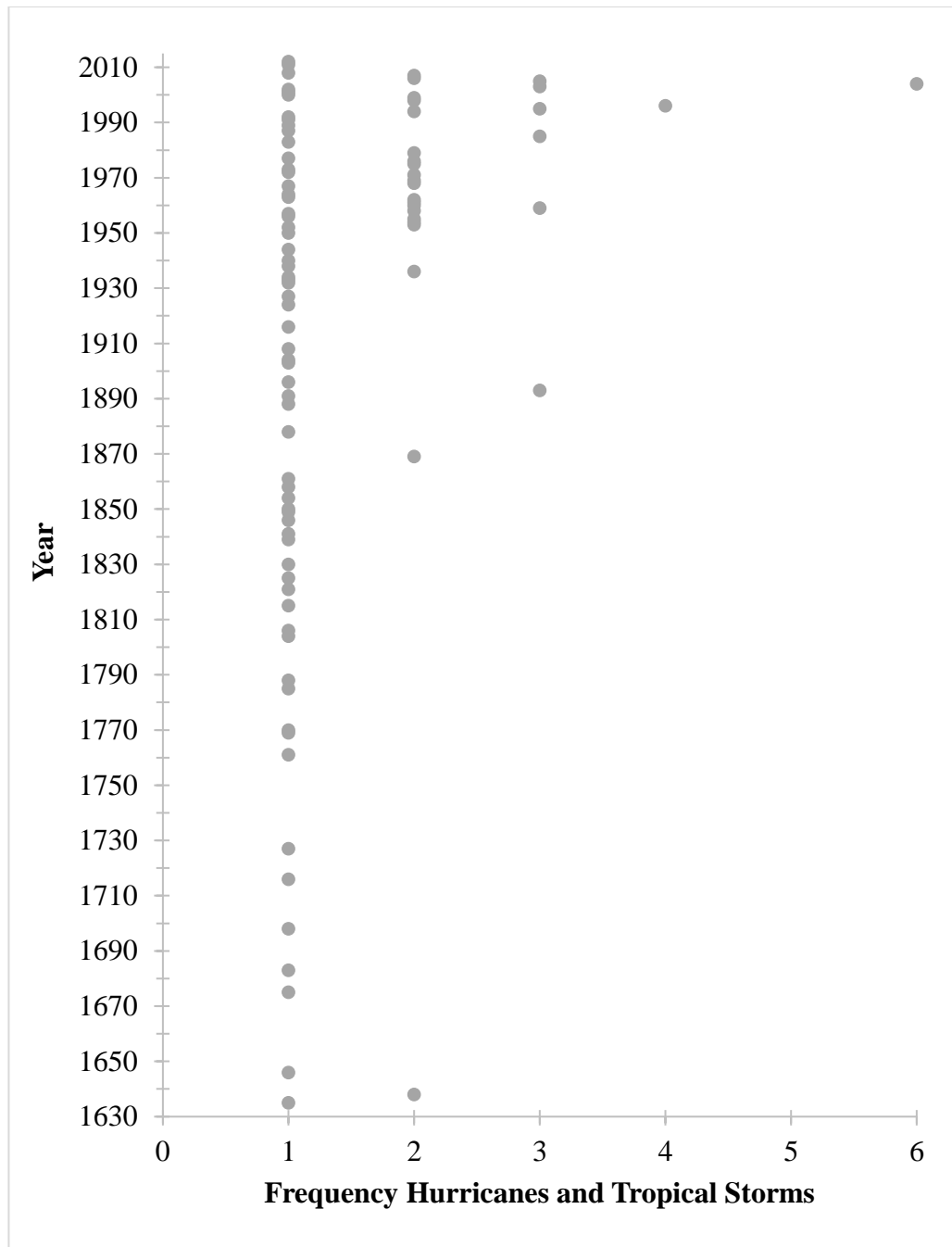


Figure 6: Frequency of hurricanes and tropical storms in the New England region. Sources include articles by Boose et al. 2001 and Donnelly et al. 2001 and records maintained by the National Oceanographic and Atmospheric Administration (NOAA).

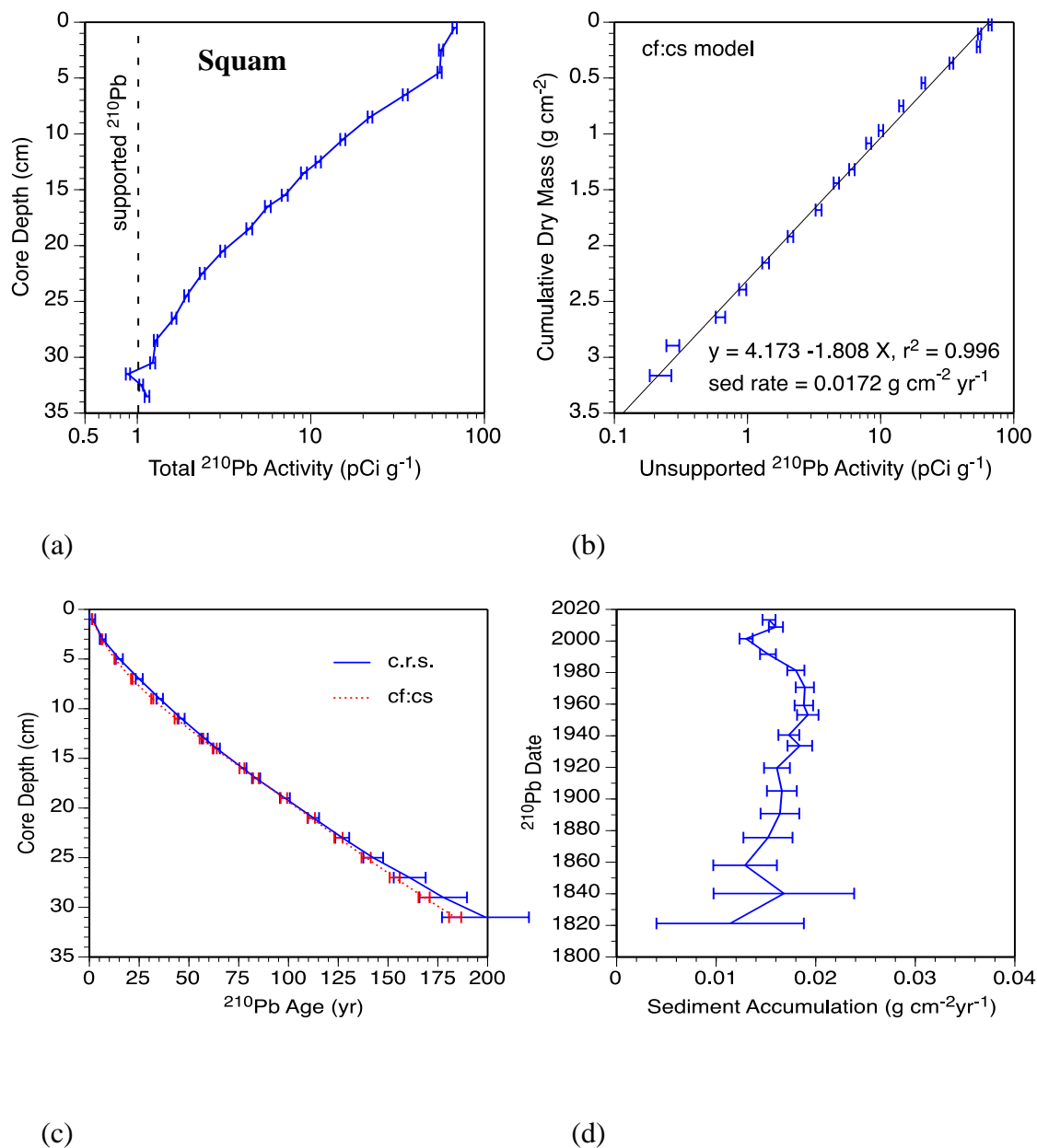
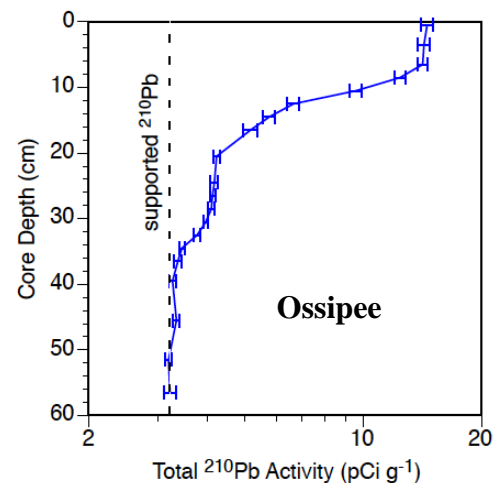
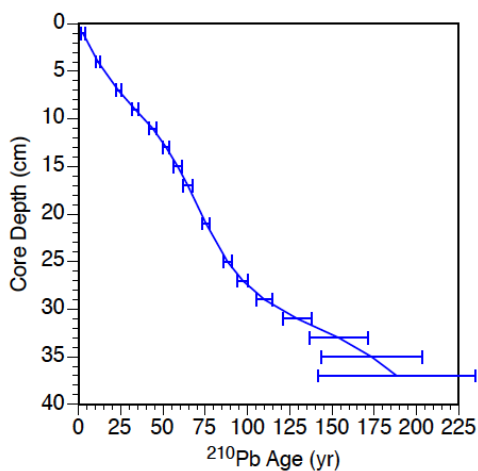


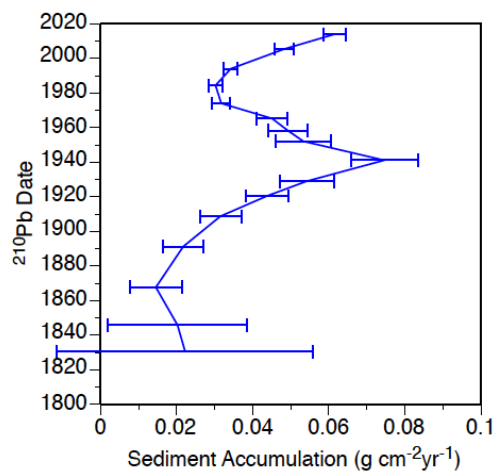
Figure 7. ^{210}Pb results from Squam 2013-1 core: (a) ^{210}Pb activity versus depth with background activity marked by the dotted line, (b) ^{210}Pb activity versus dry mass showing near linear fit using the constant flux, constant supply model, (c) ^{210}Pb age in years prior to A.D. 2013 versus core depth showing close agreement between both constant flux, constant supply and constant rate of supply models, (d) sediment accumulation rates versus date. Of note are the steady increase in sediment infilling from A.D. 1844-1949 and the decrease in after A.D. 1978. Error bars indicate the error in dating age ($\pm\text{SD}$).



(a)



(b)



(c)

Figure 8: ^{210}Pb results from Ossipee 2015-1 core. Error bars indicate the error in activity and calculated age ($\pm\text{SD}$): (a) ^{210}Pb activity versus depth with background activity marked by the dotted line, (b) ^{210}Pb age in years prior to A.D. 2015 versus core depth using constant flux, constant supply models, (c) sediment accumulation rates versus date. Of note are the steady increase in sediment infilling from A.D. 1844-1949 and the decrease in after A.D. 1978.

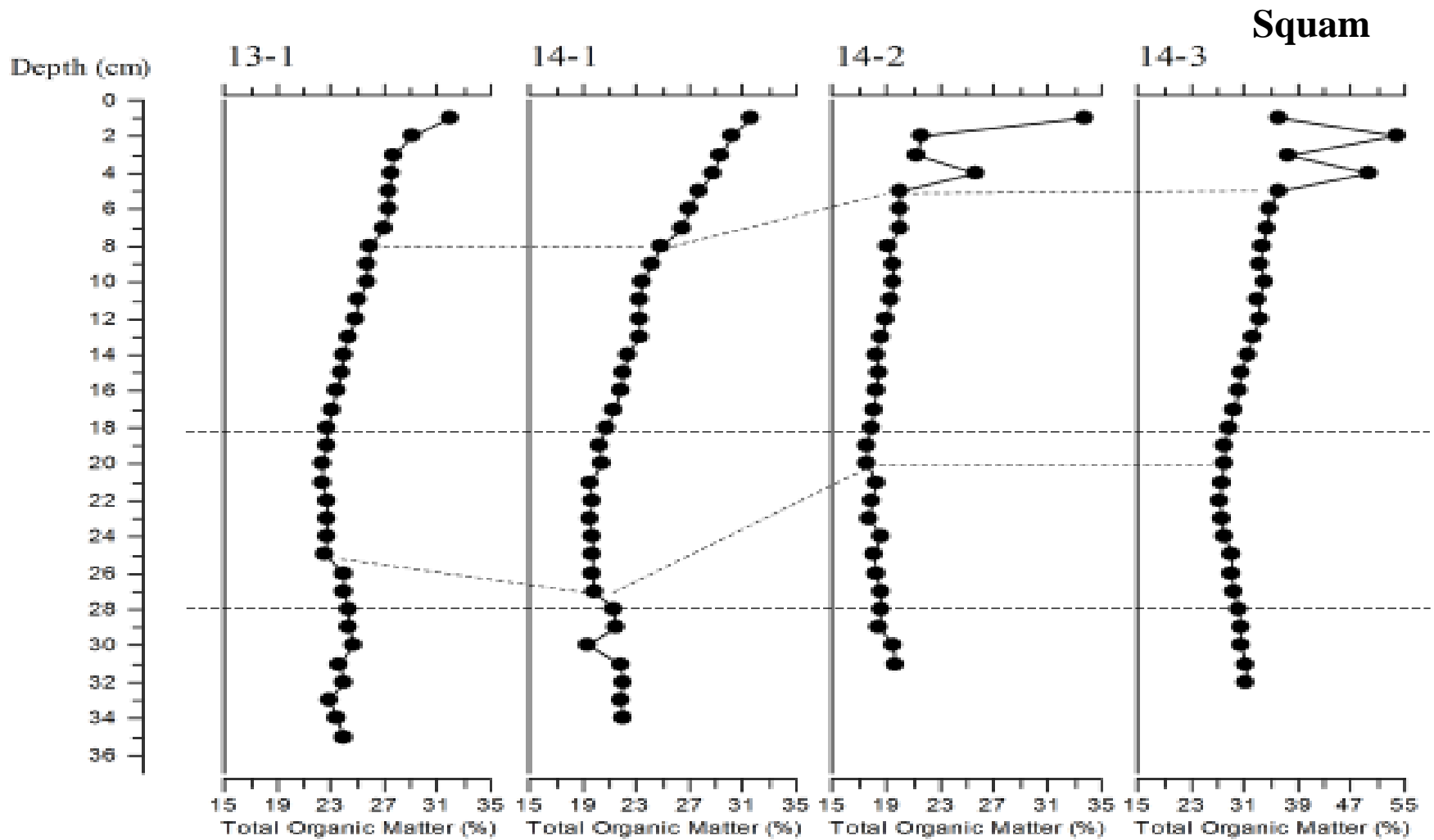


Figure 9: Comparison of total organic matter (%) determined by loss on ignition results for all Squam cores collected. Core names include the year the cores were collected (13 or 14) and then numbered sequentially.

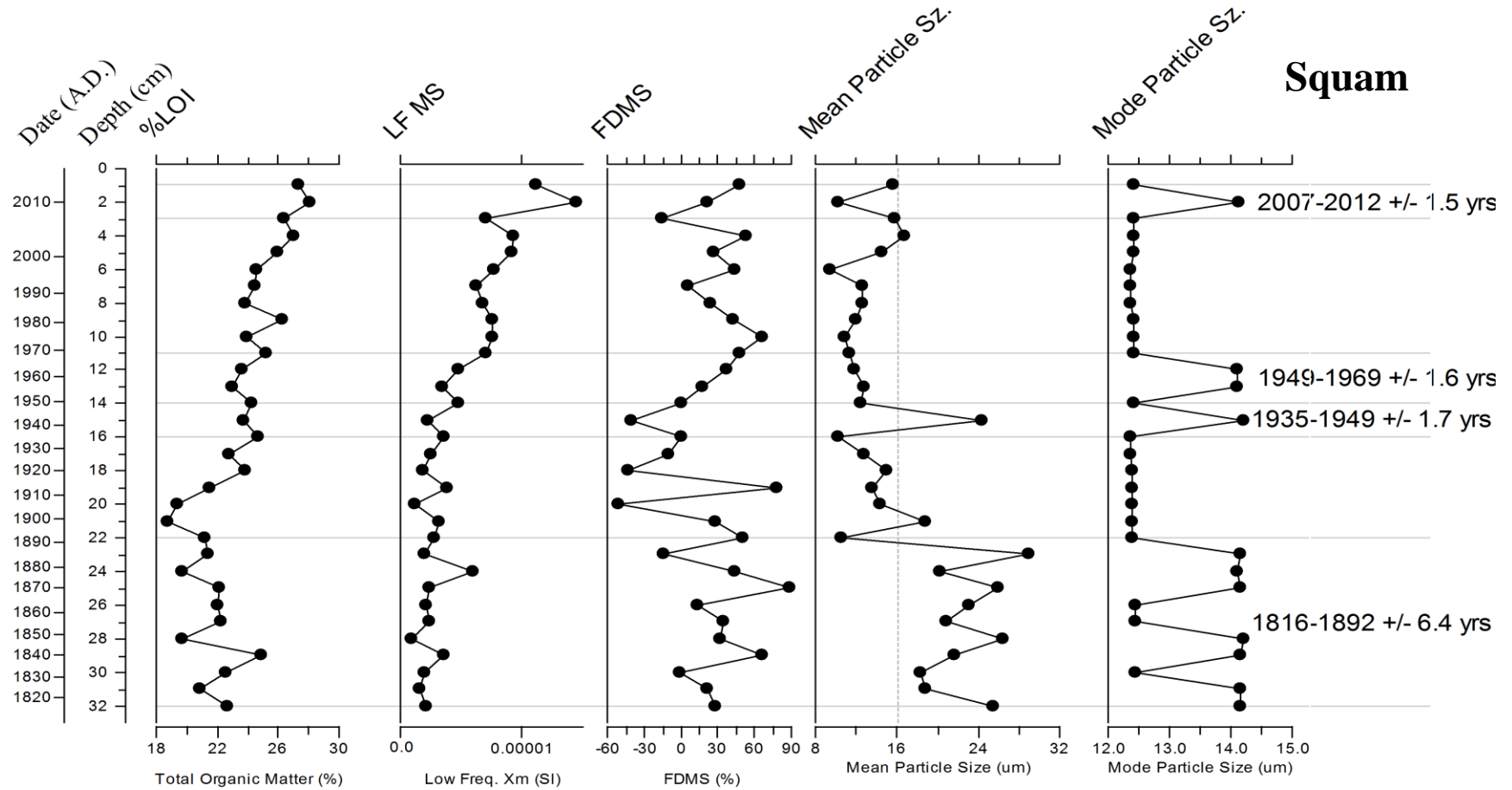


Figure 10: Organic content as loss on ignition (%), low frequency magnetic susceptibility, frequency dependent magnetic susceptibility (%), and both mean and mode particle sizes (μm) as related to depth in the Squam 2014-3 core. Dates were calculated from ^{210}Pb analysis.

Ossipee

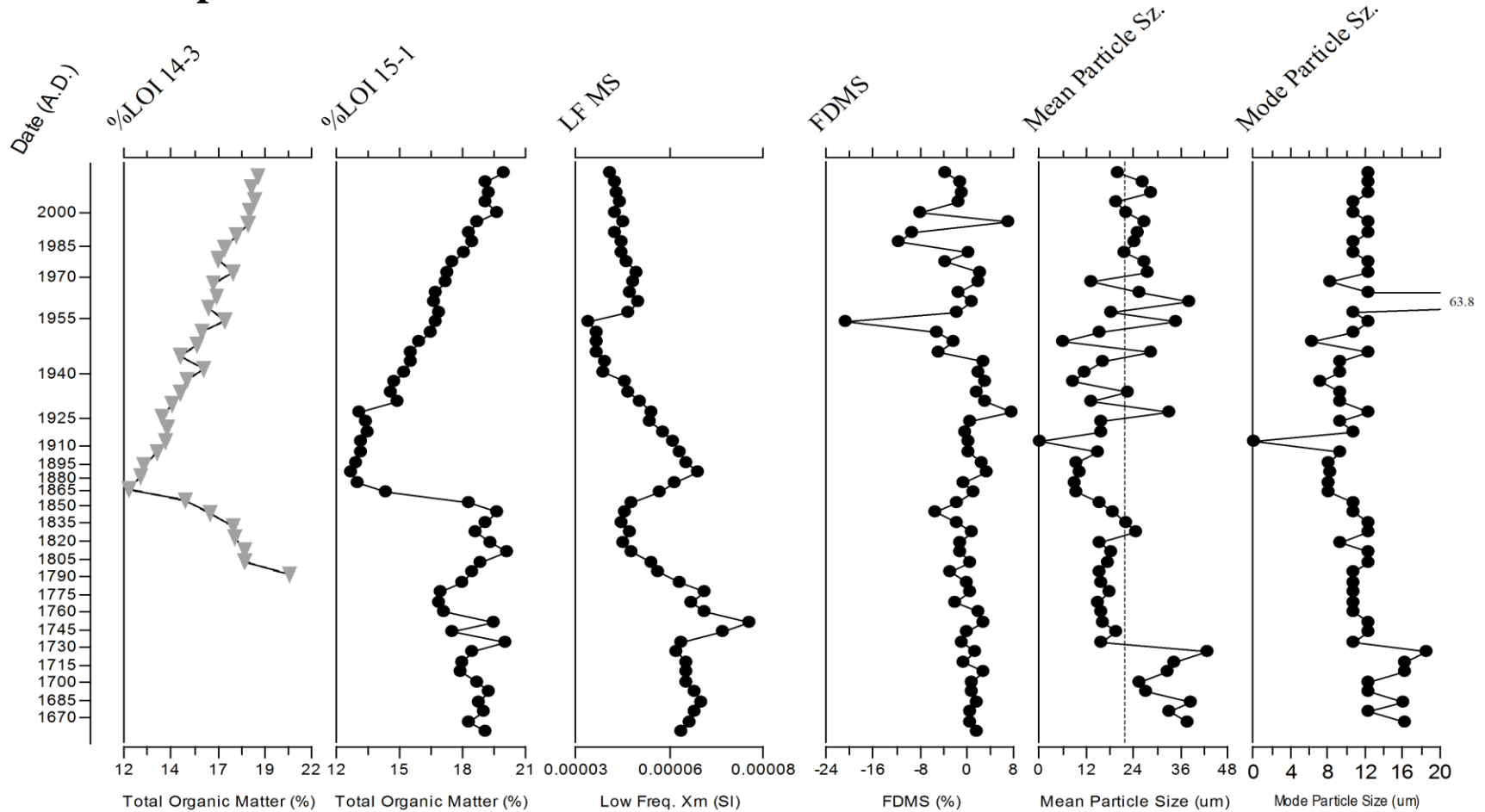


Figure 11: Organic content as loss on ignition (%), low frequency magnetic susceptibility (X_m ; SI), FDMS (%), and mean and mode particle size (μm) in Ossipee 2015-1 (right) in comparison to LOI in Ossipee 2014-3 (gray, left). Average mean particle size is denoted with a dashed line. Note that high MS values correspond with lower LOI and particle-size values, suggesting an increase influx of finer material from circa AD 1885-1925.

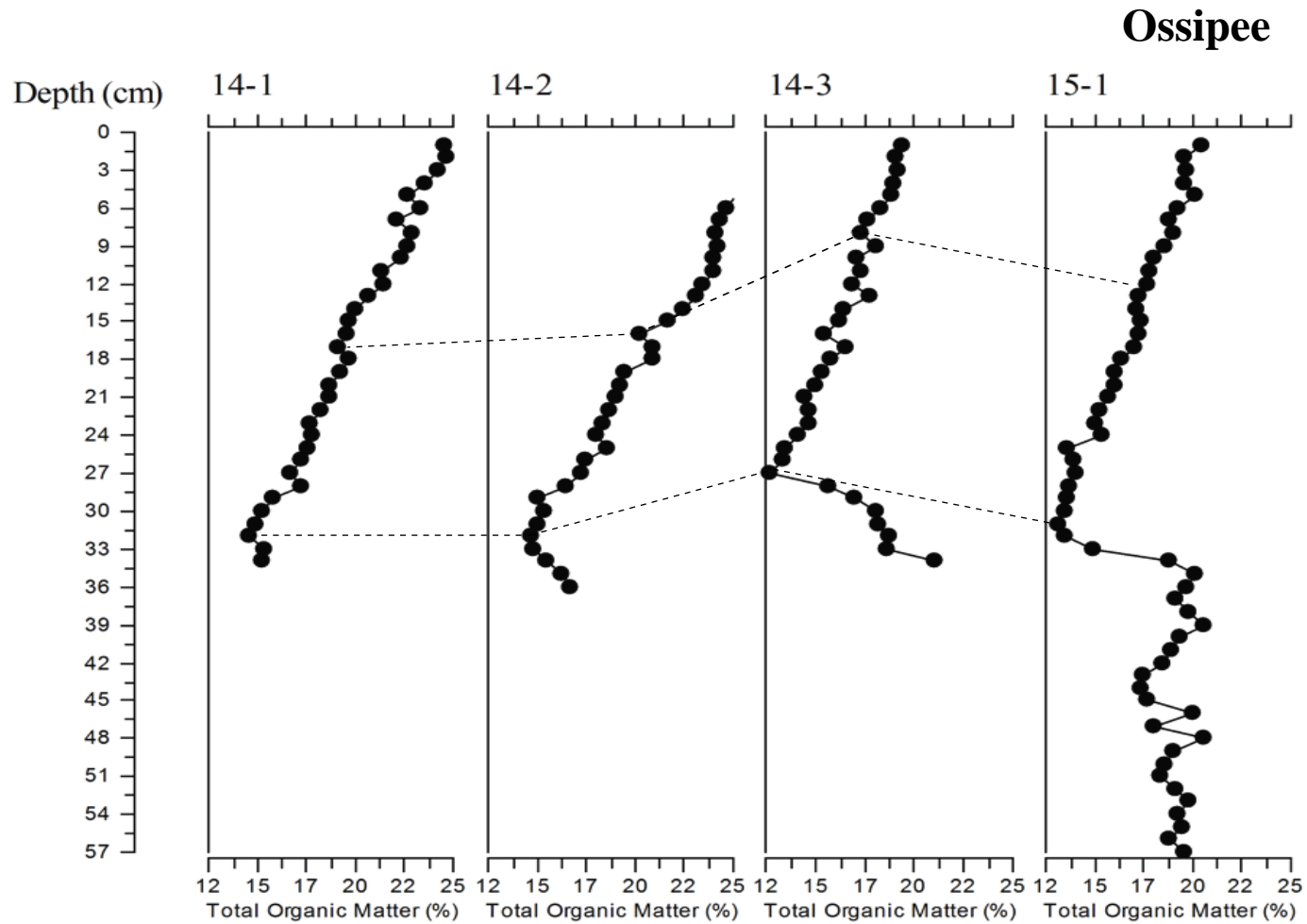


Figure 12: Comparison of total organic matter (%) determined by loss on ignition for all Ossipee cores collected. Core names include the year they were collected (14 or 15) and are numbered sequentially. These comparisons highlight the uniformity in sedimentation rates between coring sites. The apparent upward displacement of the sediments in Ossipee 14-3 probably results from loss of the core top sediments during coring, or compaction or transport.

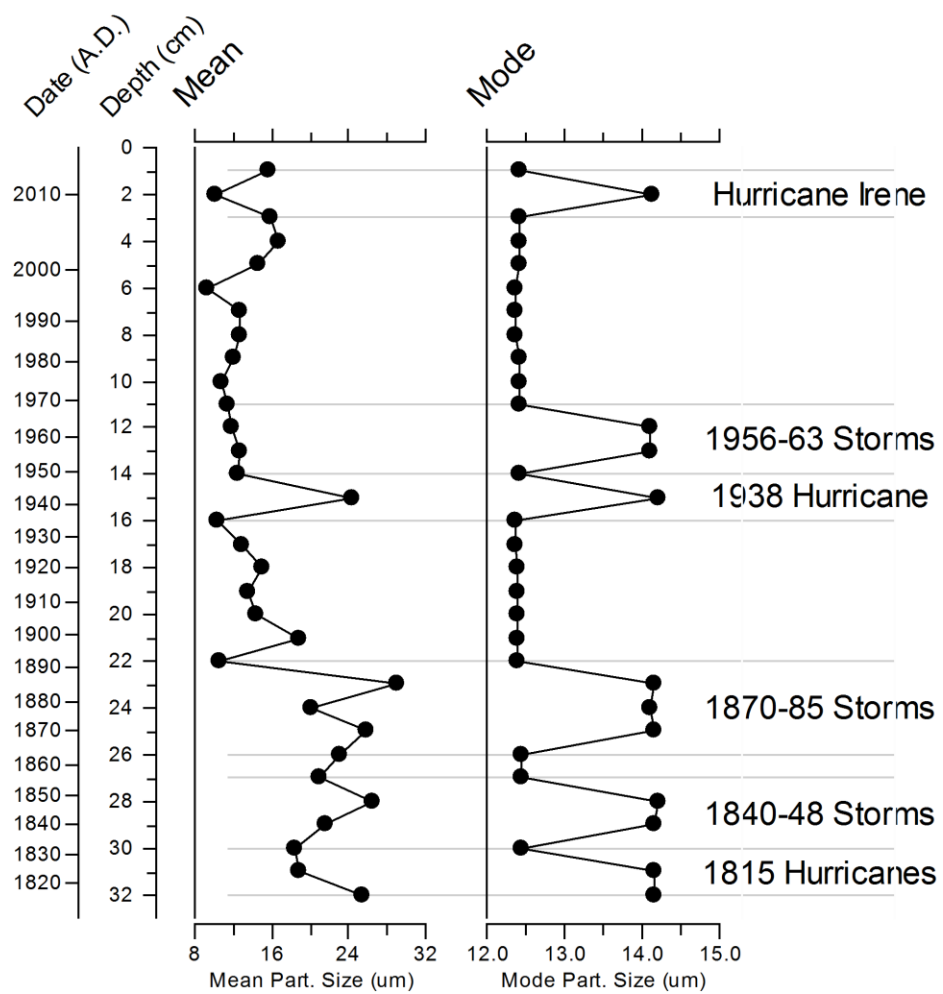


Figure 13: Correlation of variation in mean and mode particle size (μm) for Squam 2014-3 to hurricane and tropical storm events that impacted the New England region. Squam unlike Ossipee has a distinct signature for the 1938 hurricane.

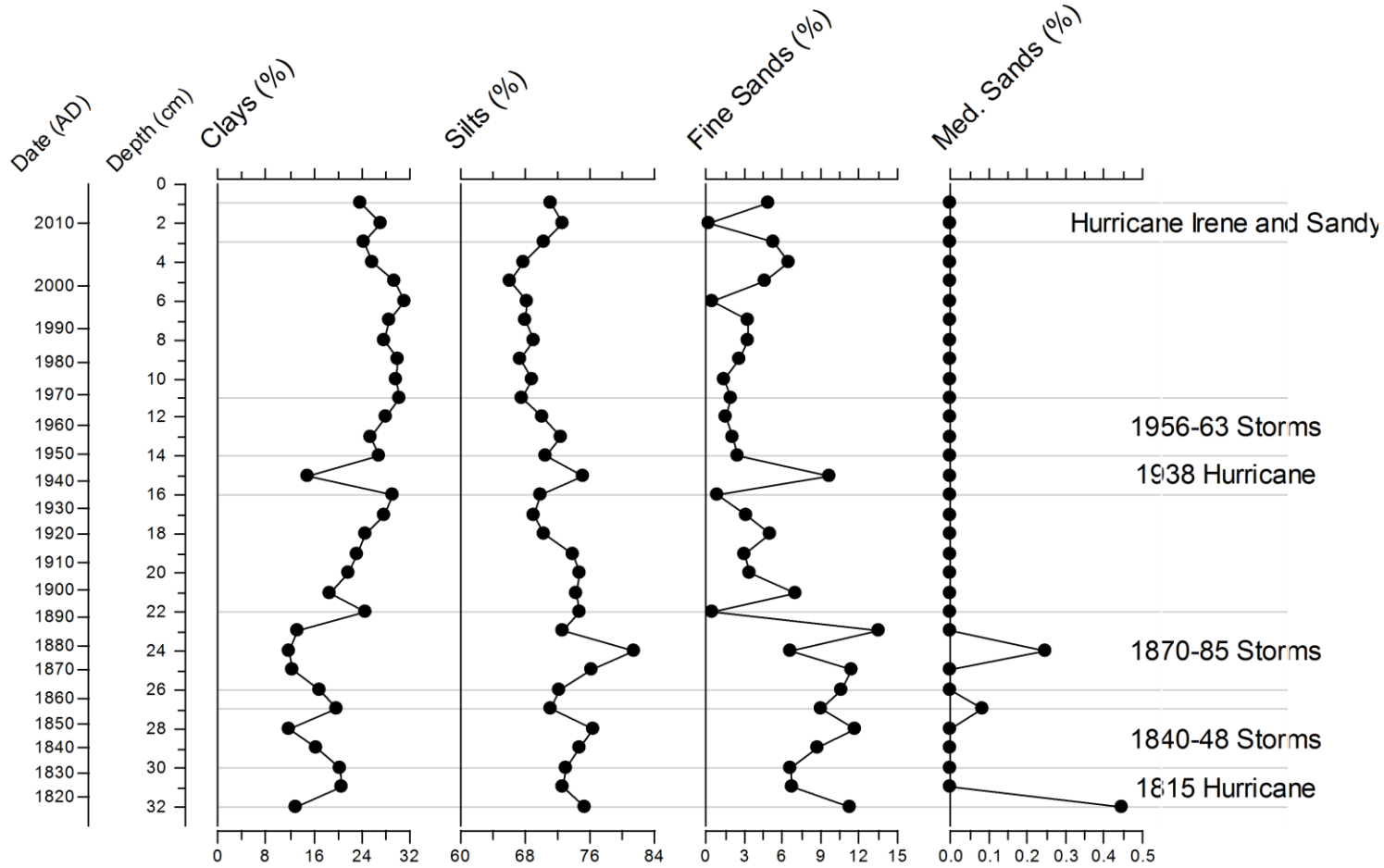


Figure 14: Classification of relative grain sizes in Squam 2014-3 core as % clays, silts, fine sands, and medium sands as defined by the Wentworth Scale against depth and ^{210}Pb derived age. Relative periods of storm events as described in figure 13 are highlighted.

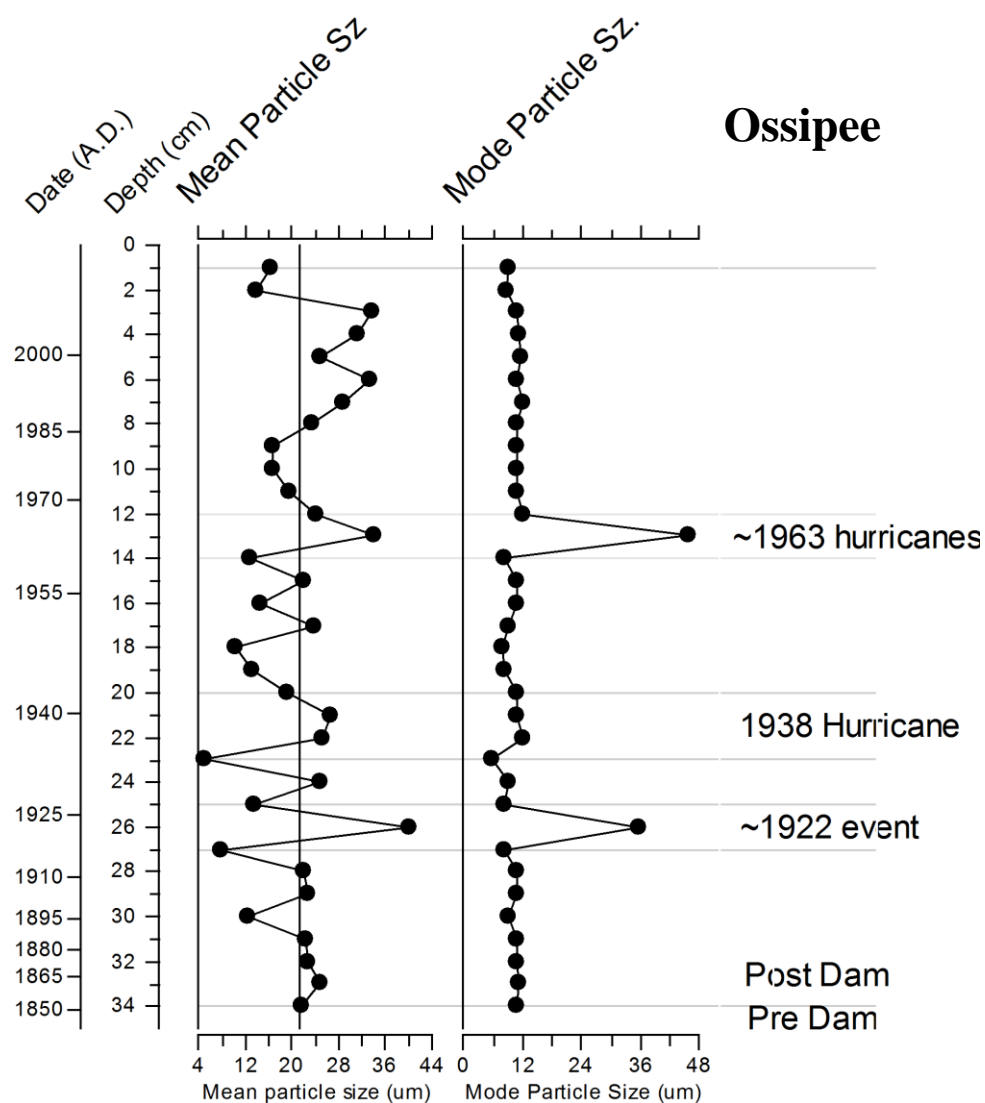


Figure 15: Correlation of mean and mode particle size events in Ossipee Lake 2014-3 core with hurricanes and tropical storms in the New England region. Dashed line represents average mean particle size through the core. Note the lack of a distinct signal from the 1938 hurricane.

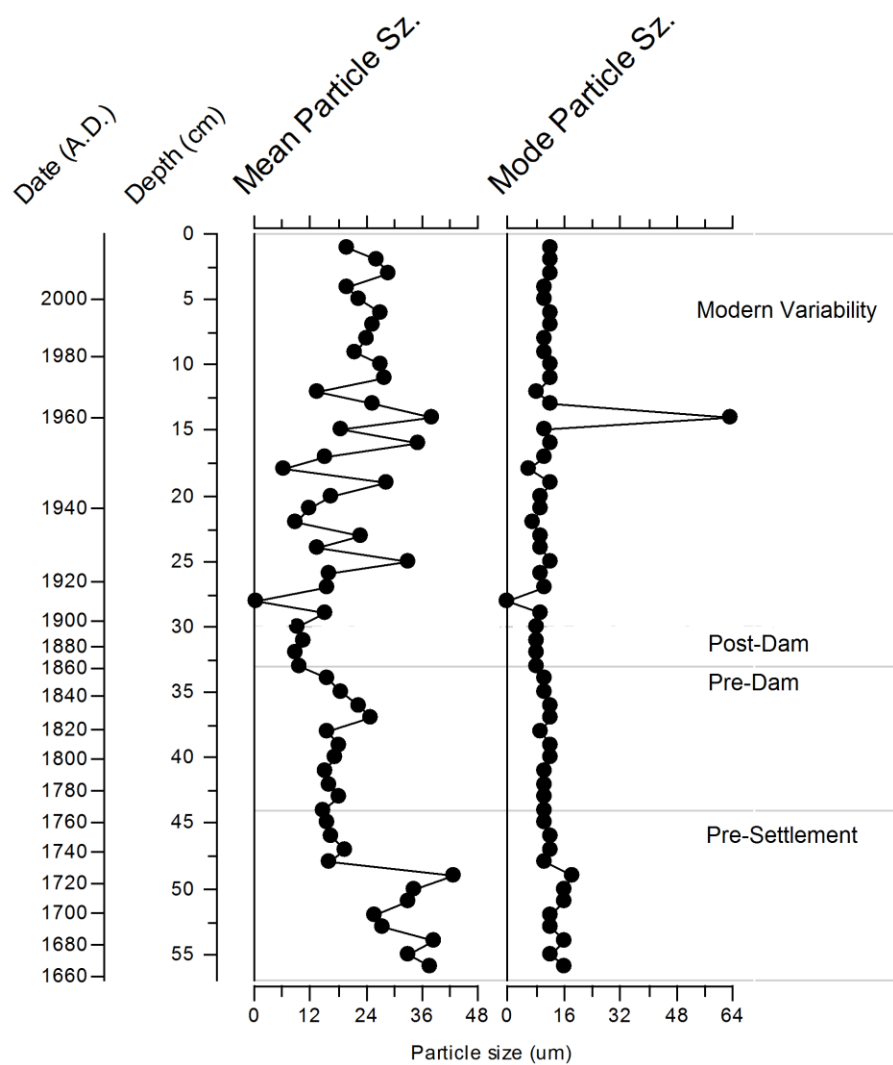


Figure 16: Mean and mode particle size transitions in Ossipee Lake 2015-1. This core shows high modern variability of grains sizes post development of the dam in the 1860s, and a period of greater mean particle sizes pre-settlement.

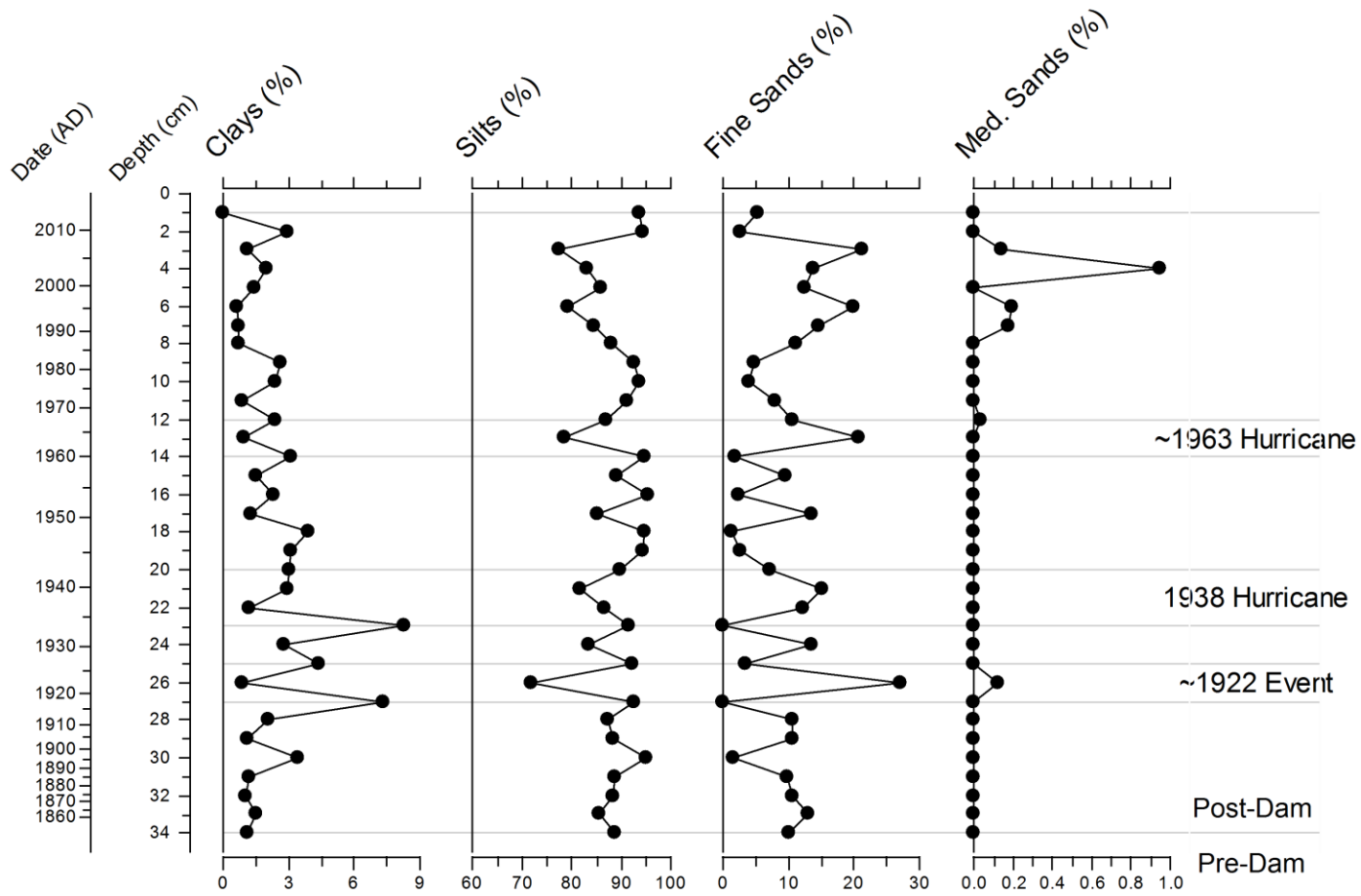


Figure 17: Classification of relative grain sizes in Ossipee 2014-3 core as % clays, silts, fine sands, and medium sands as defined by the Wentworth Scale against depth and ^{210}Pb derived age. Relative periods of storm events as described in figure 15 are highlighted.

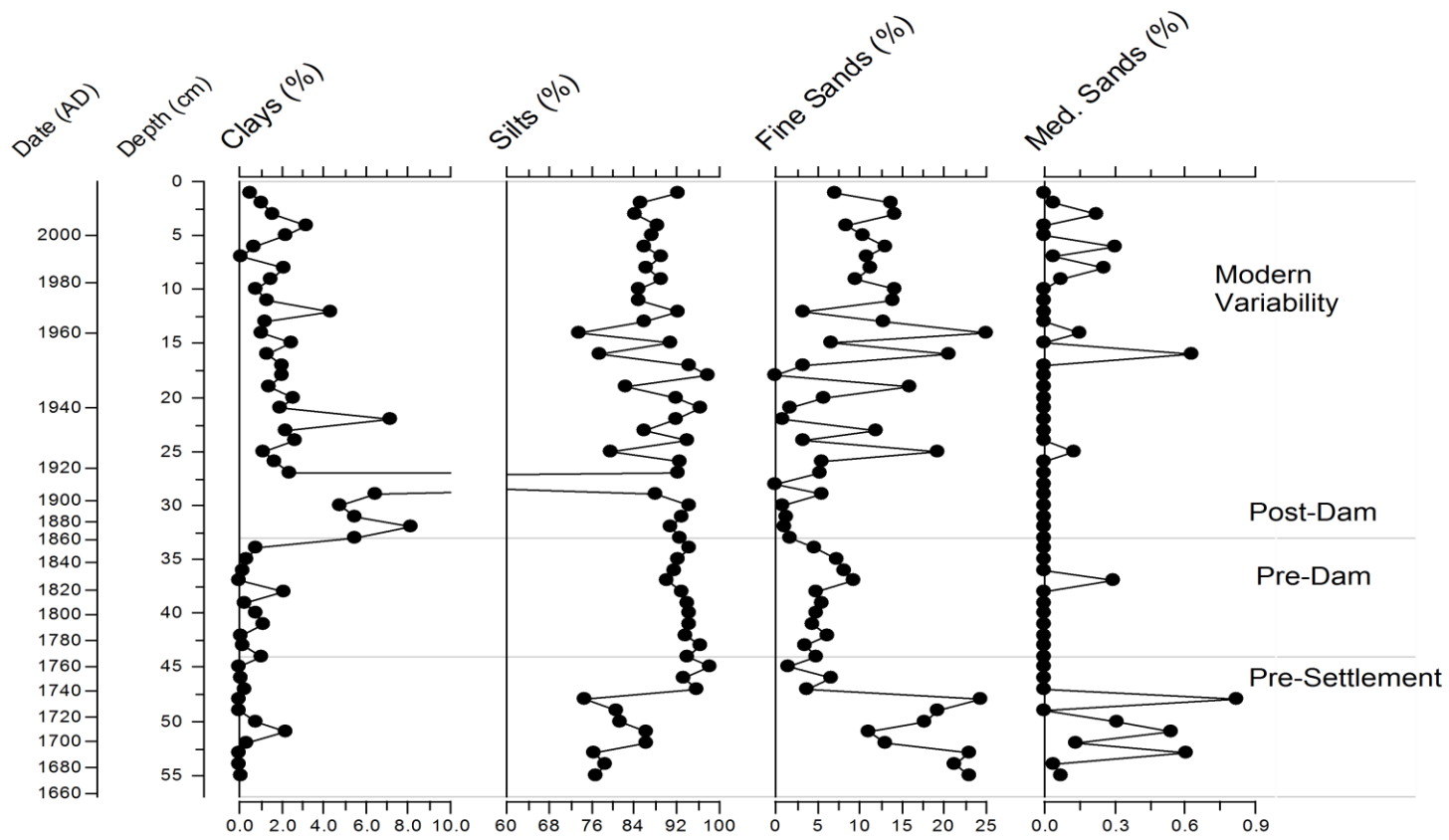


Figure 18: Classification of relative grain sizes in Ossipee 2015-1 core as % clays, silts, fine sands, and medium sands as defined by the Wentworth Scale against depth and ^{210}Pb derived age. Relative periods of storm events as described in figure 16 are highlighted.

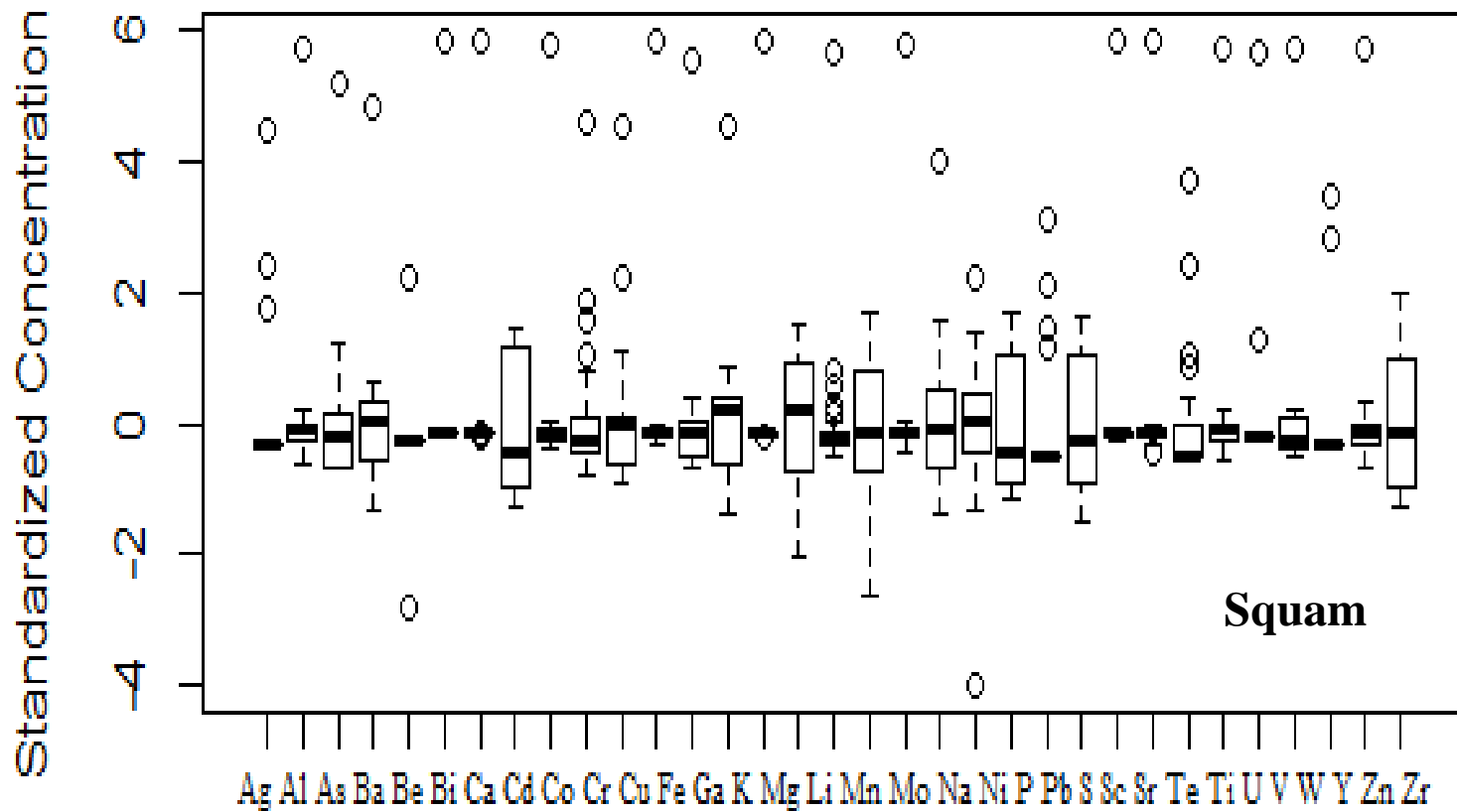


Figure 19: Box and whisker plots of the standardized concentrations of the inorganic elements within the Squam 2013-1 core. Extreme outliers (>6 standard deviation) in geochemistry are from the 1808 (± 6.4 years) sample while arsenic had its outlier in 1816 (± 6.4 years).

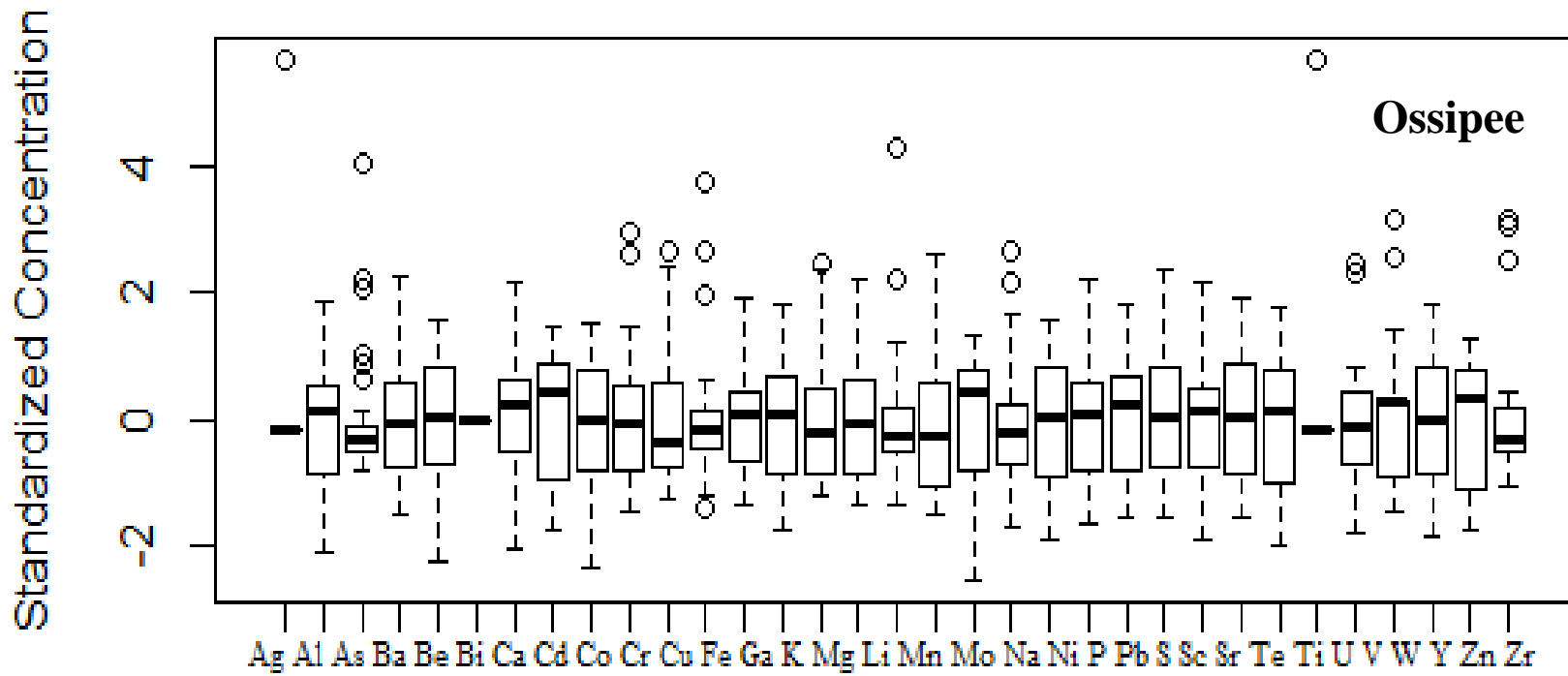


Figure 20: Box and whisker plots of the standardized concentrations of the inorganic elements within the Ossipee 2014-2 core.

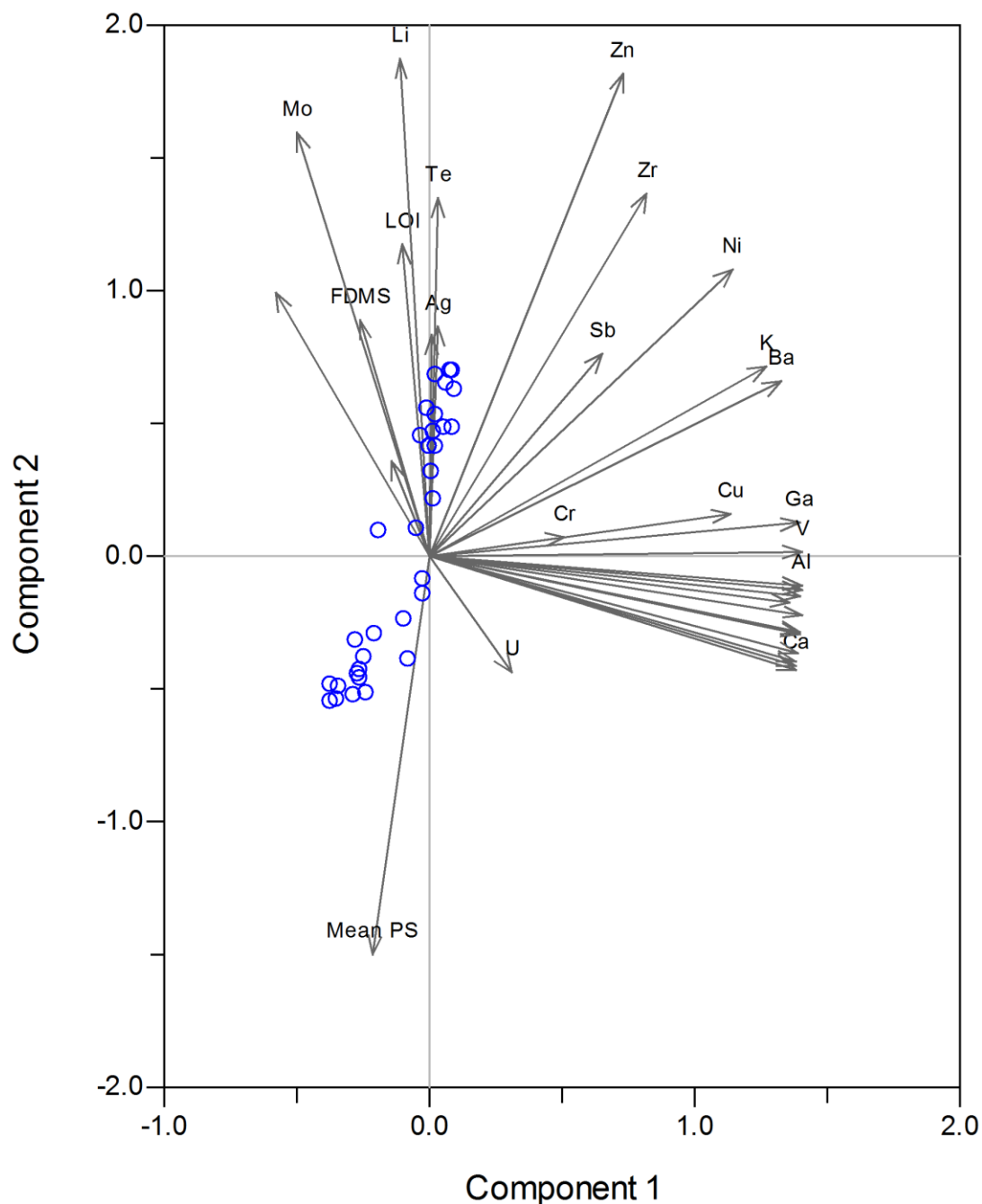


Figure 21: Biplot from PCA for Squam 2014-3 select variables. Analysis includes LOI, mean particle size, FDMS, and select inorganic geochemistry. All data are standardized. Blue circles represent discrete sediment samples. Eigen vectors show the grouping of geochemistry with the four primary species: particle size, FDMS, and LOI.

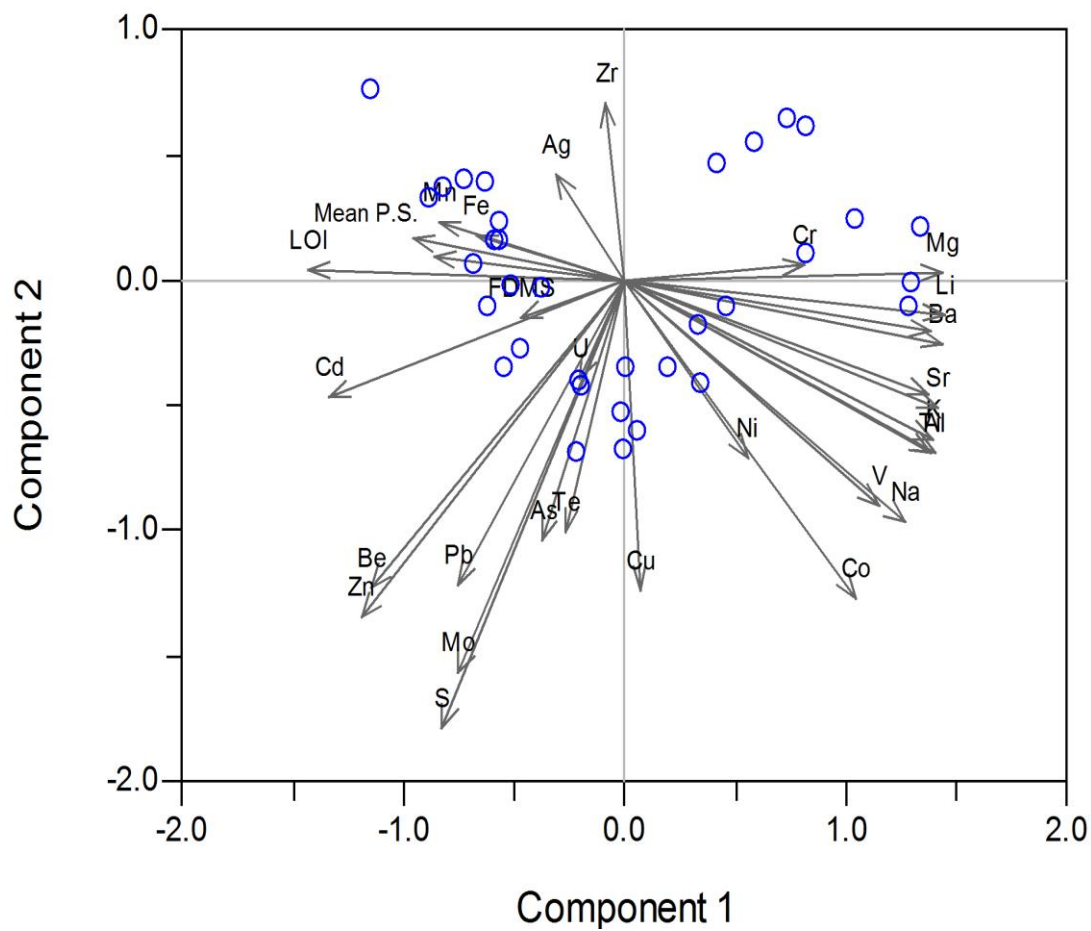


Figure 22: Biplot from PCA for Ossipee 2014-2 and 2015-1 select variables. Analysis includes LOI, FDMS, and select inorganic geochemistry are all from the 2014-2 core while particle size mean values are from the 2015-1 core. Blue circles represent discrete sediment samples. All data are standardized. Eigen vectors show the grouping of geochemistry with the four primary species: particle size, FDMS, and LOI.

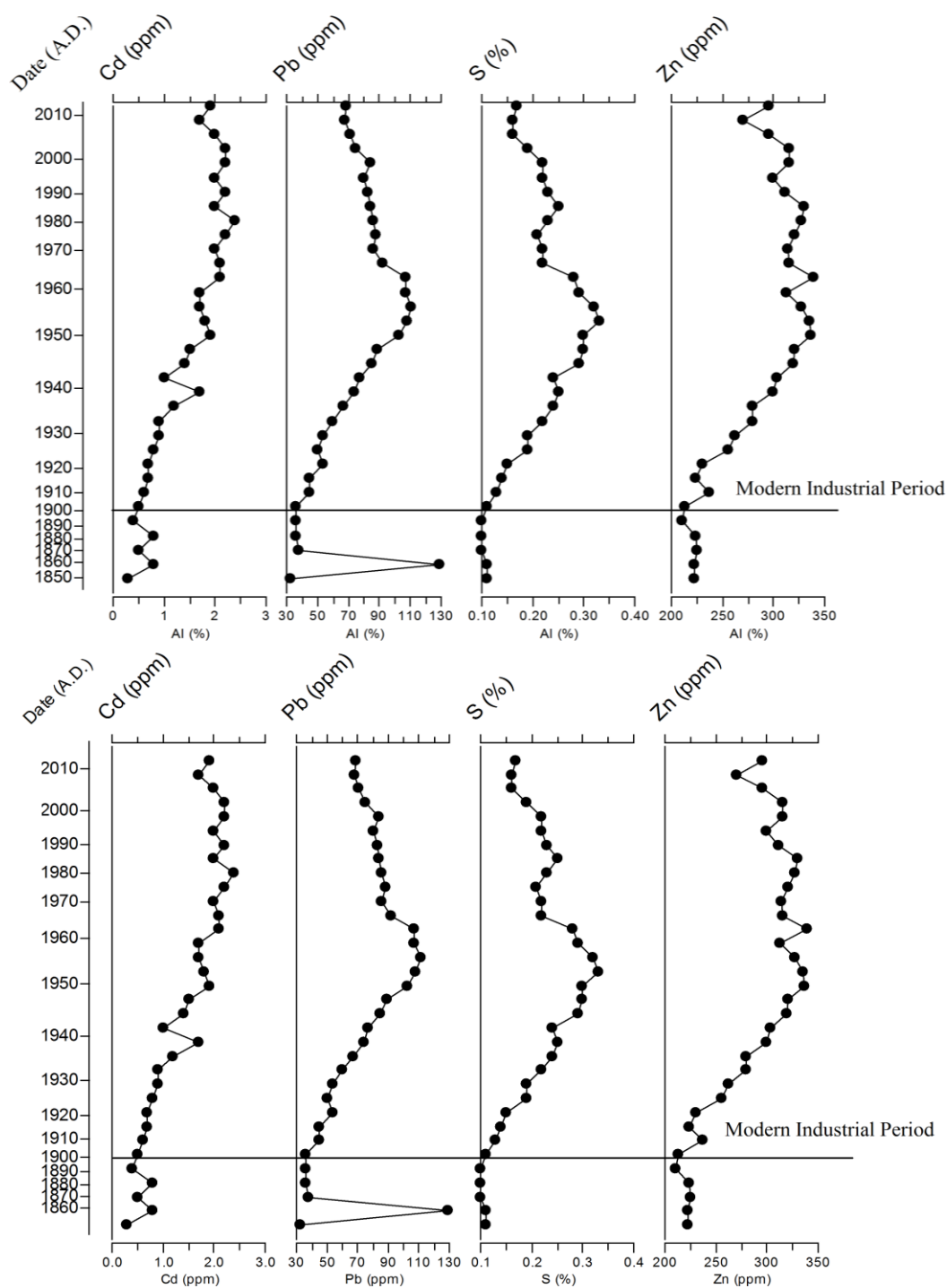


Figure 23: Relative concentrations of select elements from the ICP-OES geochemistry analysis of the Squam 2013-1 core (top) and the Ossipee 2014-2 core (bottom). Time period suggests that these are the result of industrial activities in the region.

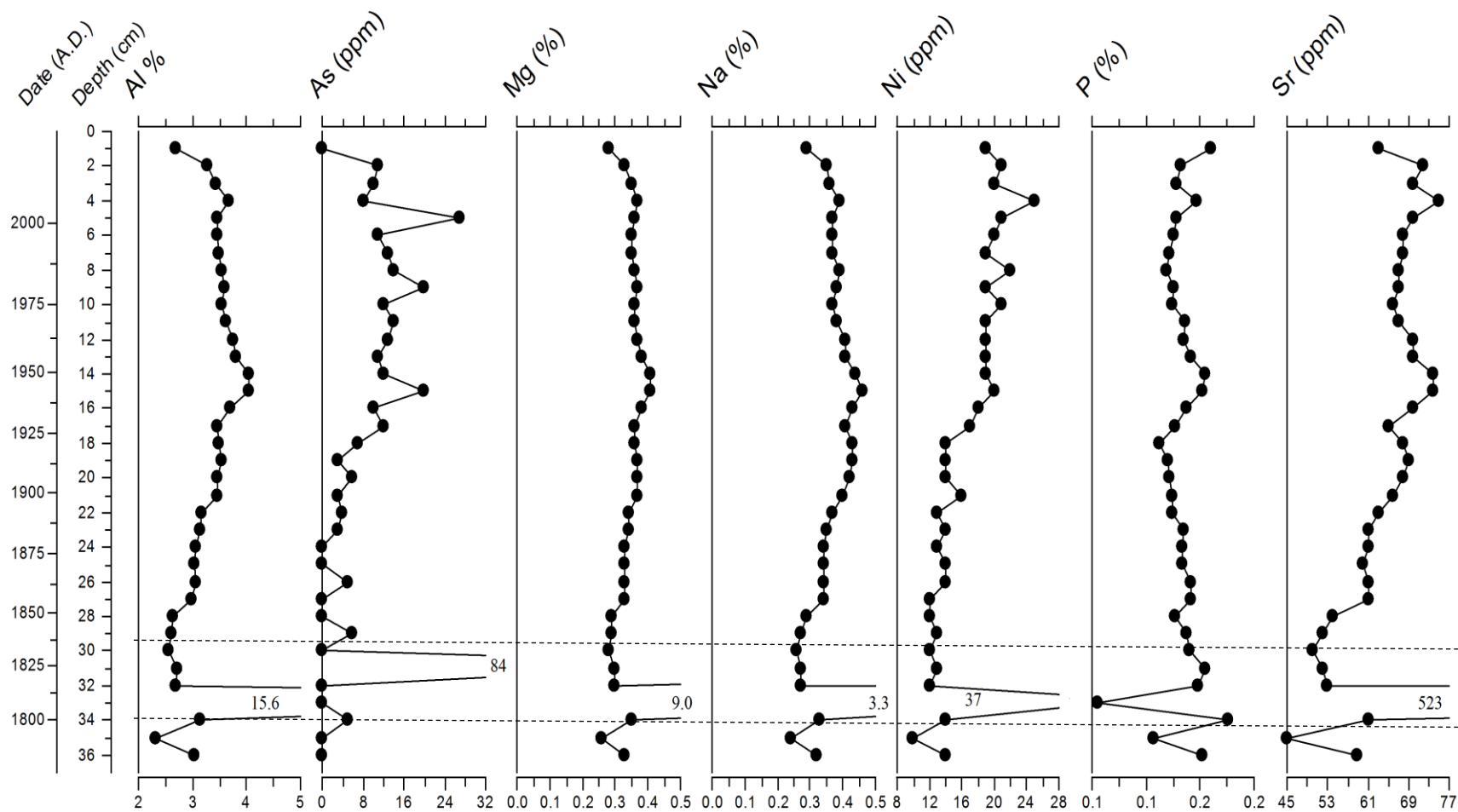


Figure 24: Relative concentrations of select elements from the ICP-OES geochemistry analysis of the Squam 2013-1 core. This figure illustrates relative changes in elemental concentration during a period between 1808 and 1816. Note the step change in As, Ni and P after 1926, similar to the timing of changes in Fig 12, in both Squam and Ossipee lakes.

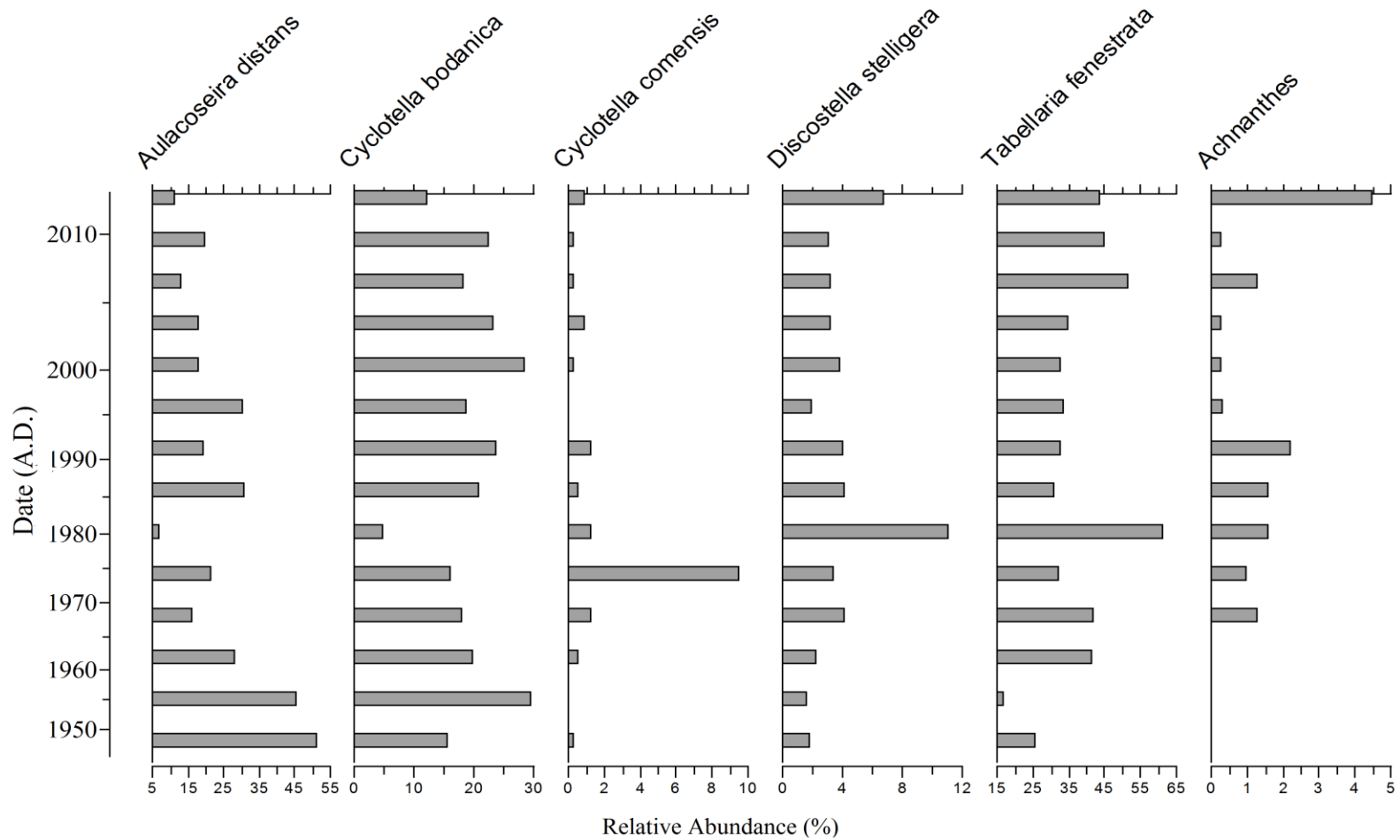


Figure 25: Relative abundance of select (>5%) species and genera of diatom fossils found in lake sediments of Squam Lake 2014-3 core. All genera and species observed are listed in the Appendix.

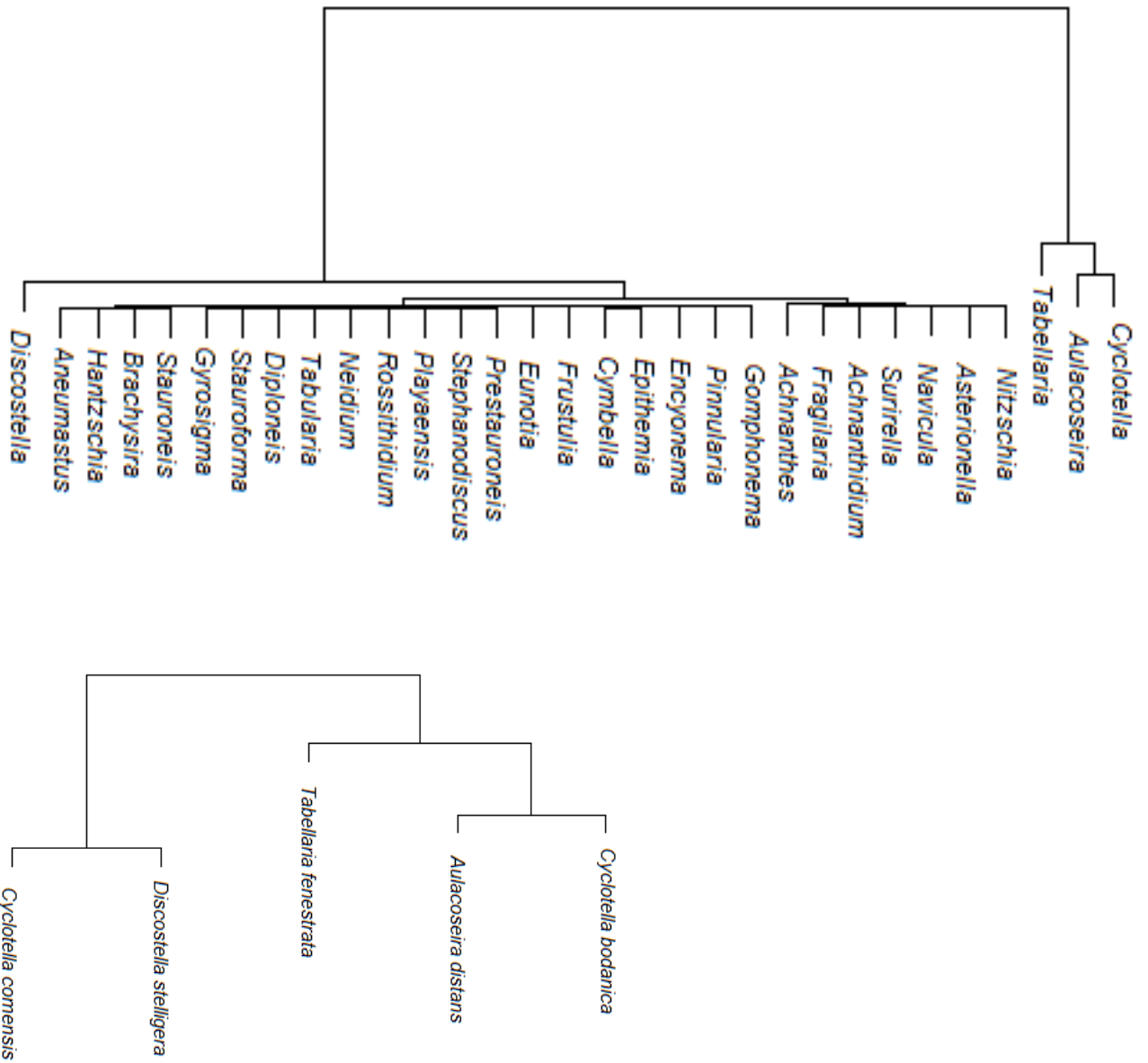


Figure 26: Cluster analysis of diatom communities found within Squam Lake sediments for all genera (a) and the 5 most abundant species (>5% abundance; b).

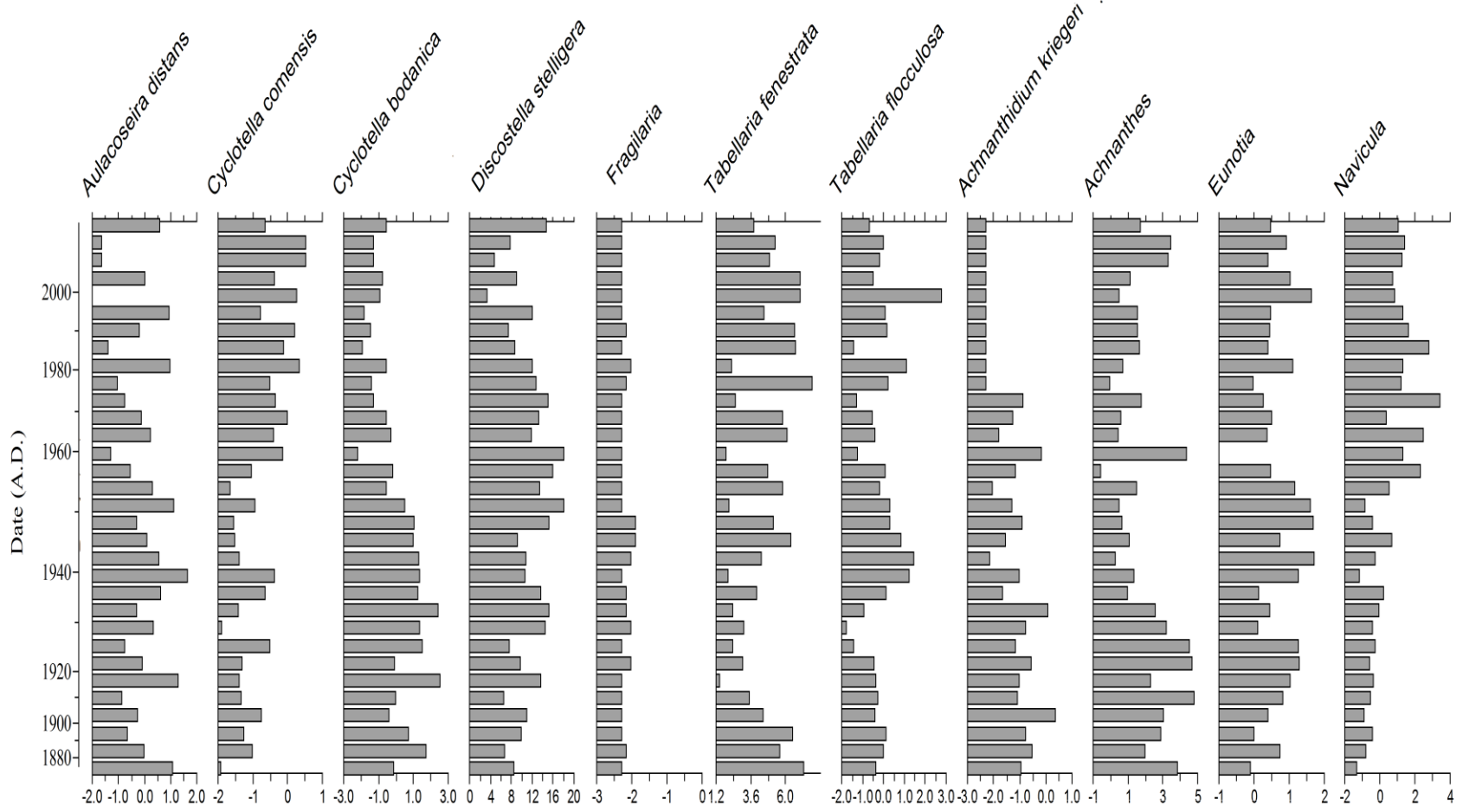


Figure 28: Relative abundance of select (>5%) genera and species of diatom fossils found in Ossipee Lake 2014-3 sediment core. All genera and species observed are listed in the Appendix.

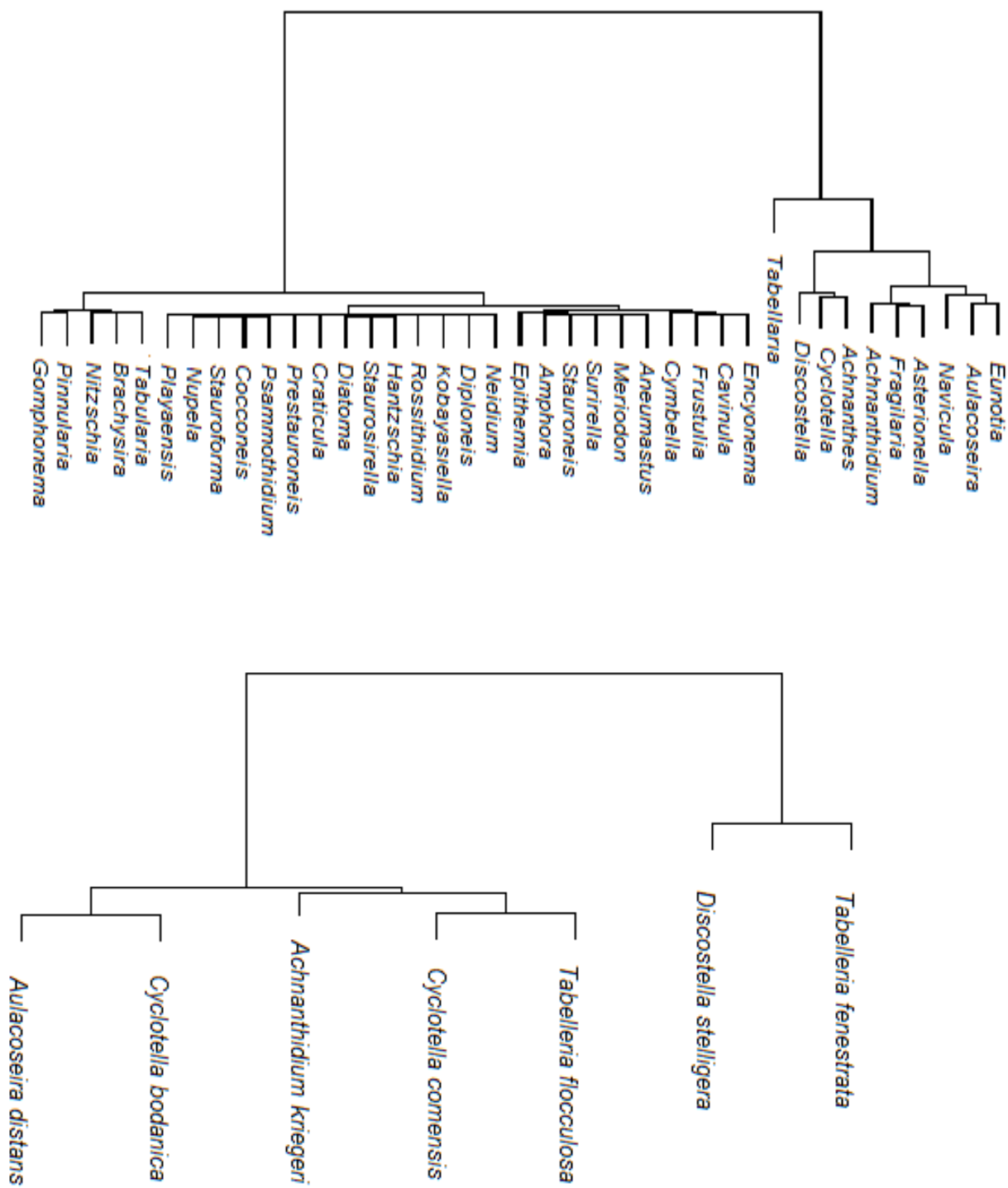


Figure 29: Cluster analysis of diatom communities found within Ossipee Lake sediments for all genera (a) and the 7 most abundant species (>5% abundance; b).

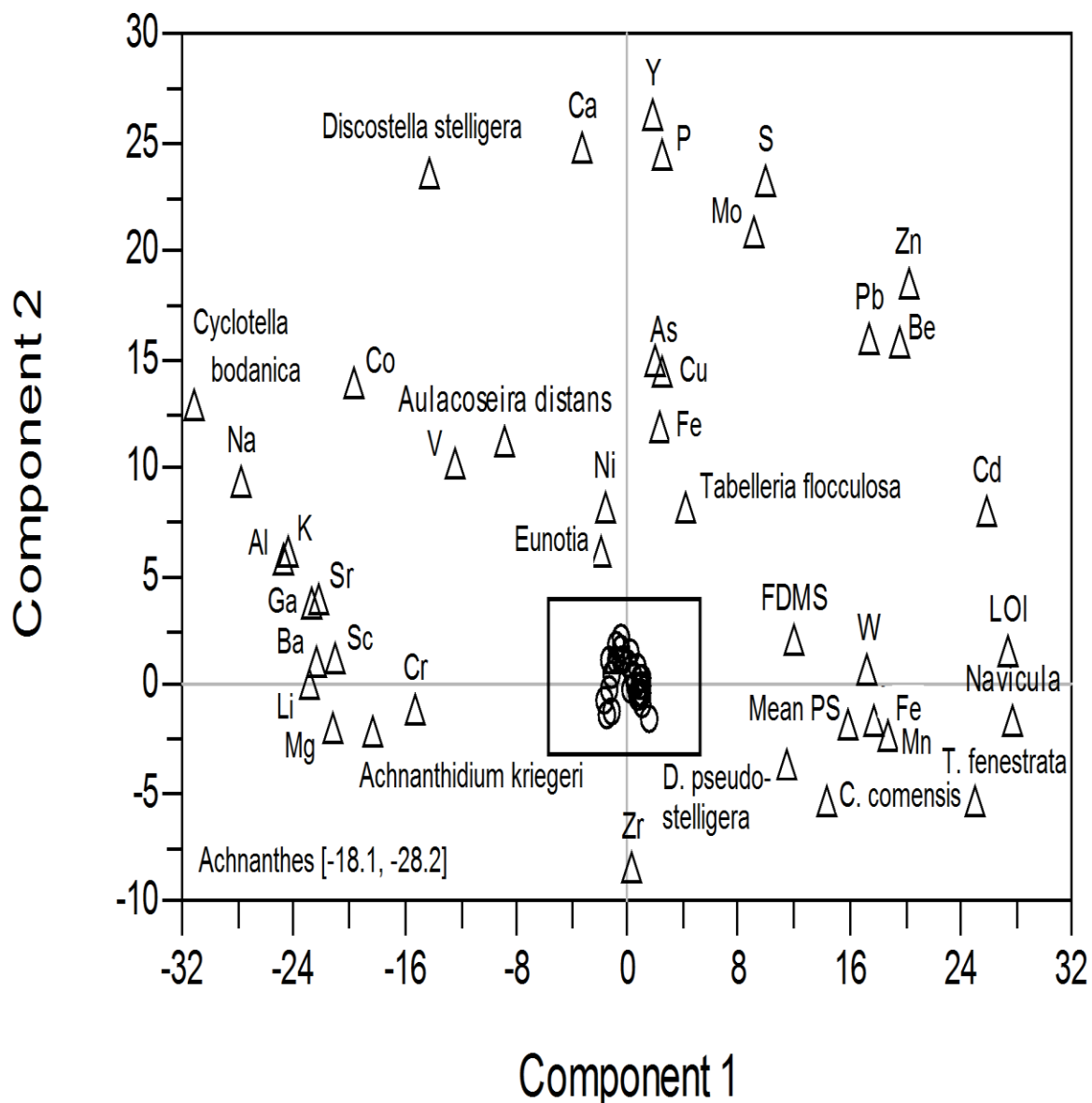


Figure 30a: Correspondence analysis for Ossipee 2014-2 and 2015-1 select variables including LOI, FDMS, inorganic geochemistry, mean particle size (μm ; labeled mean in chart), and relative abundant (>5%) diatom species between samples. Triangles represent individual variables while circles represent specific samples. The inset box of samples at the center is expanded in Figure 24b. Outlier samples are marked with their respective coordinates for components 1 and 2 [C1, C2]. All data points are standardized.

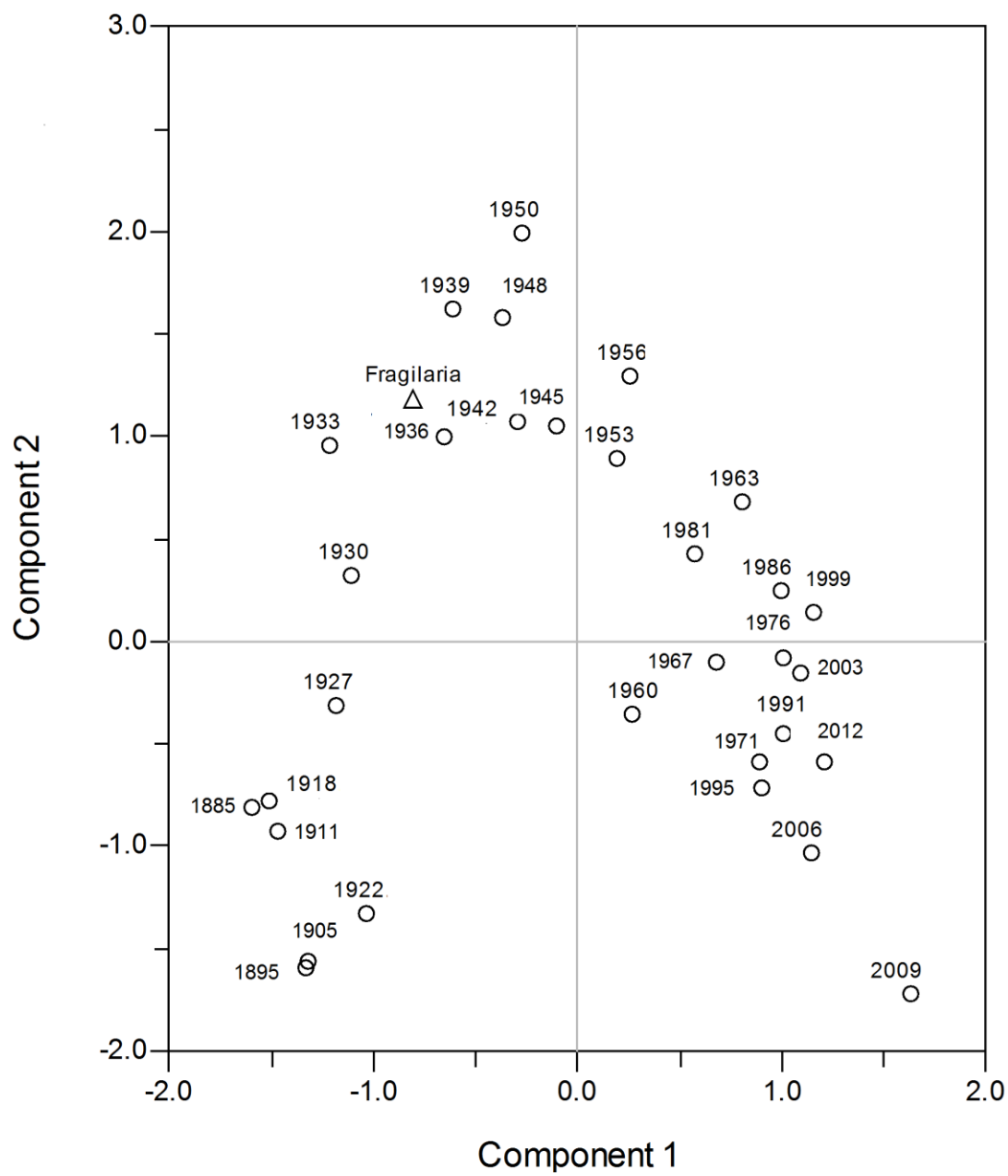


Figure 30b: Inset of central samples in correspondence analysis for select samples from Ossipee 2014-2 and 2015-1 cores as described in Figure 24a.

Conclusions

Study results show similar trends in water quality changes, recorded in the water-column and sediments of both lakes that reflect regional-scale climate-forcing rather than merely local, land-use influences. These are evidenced by the strong responses, in geochemical and particle-size data, during years with major tropical storms. These peaks are of much greater magnitude than the bulk of the record, showing that these high magnitude regional events dominate the variability in the sediment record.

We also found that water quality trends evident in the upper sediments of both lakes reflect the influences of recent climate change. The sediments of the last 15 years are distinctly different in chemical, physical and biological characteristics than all the older sediments. Further, land-use records do not indicate particularly large changes in the watersheds since 2000 AD, but climatic records show distinct trends in increased precipitation and frequency of storms in the last 15-20 years (*ie.* Douglas and Fairbank 2010, Guilbert et al. 2015, Huntington 2006) as well as warming temperatures (Hamburg et al. 2013).

Overall, these results suggest that climate events play a critical role in water quality of these lakes, at least so far as it relates to sediment budgets. But these are not isolated factors. The sedimentological aspects of the lake systems appear to be more vulnerable to climatic impacts during periods of heavy land disturbance, mostly by agriculture, such as occurred in the early 19th century. Squam Lake seems to be especially sensitive to storm events, possibly due to its relatively small watershed to lake area ratio. Both lakes show strong impacts from industrial atmospheric emissions as reflected in lake sediment geochemistry. Both lakes are slowly recovering from those particular impacts, while facing new challenges from growing human populations and development around the lakes.

This and similar studies are needed to assess long-term shifts in water quality in our lakes. By expanding knowledge of how human communities affect water resources, we can understand how the baseline status of our lakes is changing and improves our ability to predict impacts from changing climate and varying human disturbances. This project exemplifies how paleolimnology can be utilized in water quality studies, in addition to other more conventional monitoring techniques, to expand community knowledge of their managed lakes.

This study exemplifies the need for lake managers and conservation groups to incorporate both land use impacts and climate change susceptibility into their strategies, particularly recognizing that simultaneous impacts can have significant effects on lake water quality. Scientists and decision makers are slowly recognizing that management strategies need to be adapted to account for climate change and its

impacts, such as the influence of higher precipitation on nutrient loading (Crossman et al. 2013). This is understandably difficult due to varying predictions of the exact level of impact from changing climate on lakes (Wilby et al. 2010), but general strategies can still be made while taking into account how these plans can affect community resilience (Adger et al. 2011). Integrating future climate scenarios into projections of nutrient loading, land use, and water quality in both lake and watershed management plans is the next step to addressing this issue and recognizing where current methods and programs need adaptations.

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Appendices

All supplemental information for this thesis is permanently archived on Mahara Portfolio at Plymouth State University. Access the portfolio at: <http://www.plymouth.edu/eportfolio/view/view.php?t=r6no9d7bZ0wBzKYPRiGx>