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Research Article

12,000 years of landscape evolution in the southern White Mountains, New Hampshire, as recorded in Ossipee Lake sediments

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Abstract

Continuous records of sediment yield spanning from the late glacial through the Holocene to the present day provide an important opportunity to investigate landscape evolution over various timescales in response to a variety of natural and anthropogenic forcing mechanisms. This study investigates variations in sediment yield and landscape evolution in the 768 km^2 watershed of Ossipee Lake, New Hampshire, USA. We pair subbottom sonar observations with analyses of lacustrine sediment cores to interpret a 12,000+ yr record of lake sedimentation in terms of changes in sediment yield and landscape evolution. Our results indicate high rates of sediment redistribution following deglaciation at ~14,500 to ~12,000 cal yr BP, followed by a period of gradually decreasing sediment yield until ~9000 cal yr BP, marking the termination of the most intense period of paraglacial landscape adjustment. From 9000 cal yr BP to 1850 CE, sediment yield is highly variable and reveals a slightly increasing trend that we attribute to a dominant hydroclimatic control on erosion driven by increasing effective precipitation in the region throughout the Holocene. Despite evidence for a highly dynamic landscape and an abundance of unconsolidated glacigenic surface deposits throughout the watershed, we interpret a modest erosional impact from anthropogenic land use.

Keywords: Paleolimnology, Geomorphology, Proglacial landscape evolution, Holocene, Proglacial, Paraglacial

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INTRODUCTION

A legacy of Pleistocene glaciations in the northeastern United States is a widespread, but variable mantle of sediment covering much of the landscape (Hitchcock, 1878; Goldthwait et al., 1951). Following deglaciation, the rate at which this material has been redistributed has been influenced by paraglacial landscape adjustments, changing hydroclimatic conditions, and human activities (e.g., Bierman et al., 1997; Francis and Foster, 2001; Cook et al., 2015, 2020). Considering this redistribution of sediment in terms of watershed sediment yield has direct implications for understanding fundamental processes related to soil erosion, contaminant transport, reservoir life span, and the delivery of sediment to coastal systems. The post-glacial landscape evolution of the northeastern United States is relevant to our understanding of previously glaciated landscapes throughout the world and is particularly germane to understanding how mountain landscapes and their associated geologic hazards may evolve under conditions of global warming and glacial recession, as is happening currently in many locations (Knight and Harrison, 2018).

Quantifying sediment yield and its response to various forcings is especially challenging, given the need for measurements spanning a wide range of hydroclimatic conditions (e.g., Croke and Hairsine, 2006) and the difficulty in deciphering the impacts of simultaneous changes in climate and human activity in the recent past (e.g., Huggel et al., 2012; Kasprak et al., 2013; Cook et al., 2015). While geologic archives can capture a wide range of climatic conditions under circumstances minimally impacted by humans, many of the available archives provide only snapshots of past conditions. Sedimentary records from suitably located lakes and ponds offer the potential for long, continuous records of sediment accumulation, from which estimates of terrestrial sediment yield may be derived (e.g., Davis and Ford, 1982; Cook et al., 2020). A limited number of studies in the northeastern United States have examined sediment delivery to lakes in response to terrestrial processes; however, the majority of existing records have focused on lakes with very small (mostly <15 km^2) watersheds, lacked age control over the period most heavily impacted by humans, and revealed inconsistent patterns of sediment delivery over the Holocene (e.g., Brown et al., 2000, 2002; Noren et al., 2002; Parris et al., 2010). Two existing regional records from lakes with relatively large watersheds and recent age constraints that allow correlation of sedimentary events with historical hydrologic conditions and land-use activity span only the past 1100 (Cook et al., 2020) and 2100 yr (Cook et al., 2015), failing to capture the period of most intense paraglacial landscape adjustments and the largest climatic changes of the Holocene.

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Given the importance of understanding landscape evolution in response to changing climate and human activity, and the dearth of suitable records, we seek to answer the question: How has the erosion and transport of sediment in the northeastern United States varied since deglaciation in response to long-term trends in climate, vegetation change, past floods, and anthropogenic land use? We do so using sediment cores collected from Ossipee Lake, New Hampshire, USA. Analysis of these cores is used to reconstruct the mass accumulation rate of clastic sediment from ~12,000 cal yr BP to 2017 CE as a proxy for watershed sediment yield. Regionally, Ossipee Lake has a uniquely large watershed with limited upstream water bodies, a remarkably simple lake geometry, and an abundance of unconsolidated sediment mantling its watershed. Collectively, these traits distinguish Ossipee Lake as an ideal setting for examining the integrated signal of hydroclimatic, ecological, and anthropogenic impacts on sediment yield operating within a large watershed over various timescales and we evaluate our results in relation to regional records of climate and environmental change.

STUDY AREA

Ossipee Lake and its watershed are located in east-central New Hampshire, USA (Fig. 1). The 768 km^2 watershed ranges in elevation from 124 m at Ossipee Lake, to >1200 m along summits of the Sandwich Range of the southeastern White Mountains. Presently, the watershed is dominantly forested (78% of current land cover), with only a small portion developed (4.5%) or in agricultural use (1%; Dewitz, 2019). Thick surficial deposits surround Ossipee Lake and blanket much of the watershed, a legacy of the last glaciation and subsequent deglaciation (Newton, 1974a, 1974b). Regional deglaciation occurred around 14,500 cal yr BP (Ridge et al., 2001, 2012; Dalton et al., 2020; Ridge, 2022); during the earliest stages of deglaciation, much of the low-elevation portions of the Ossipee watershed were occupied by a proglacial lake. The size of this lake and location of its outlet shifted rapidly in concert with the retreating ice front, with the lake surface migrating through a series of steps corresponding to present-day elevations of 182 m, 171 m, and 140 m, before the current 124 m elevation of the lake was established (Moore and Medalie, 1995). Meltwater from the retreating ice front deposited proglacial lake sediments, eskers, kame deposits, and outwash plains forming what is today the largest stratified drift aquifer within the state of New Hampshire (Moore and Medalie, 1995). Upland areas of the watershed are mantled in glacial till (Newton, 1974a).

Postglacial redistribution of surface materials in the Ossipee Lake watershed is widely evident, alluding to a dynamic landscape

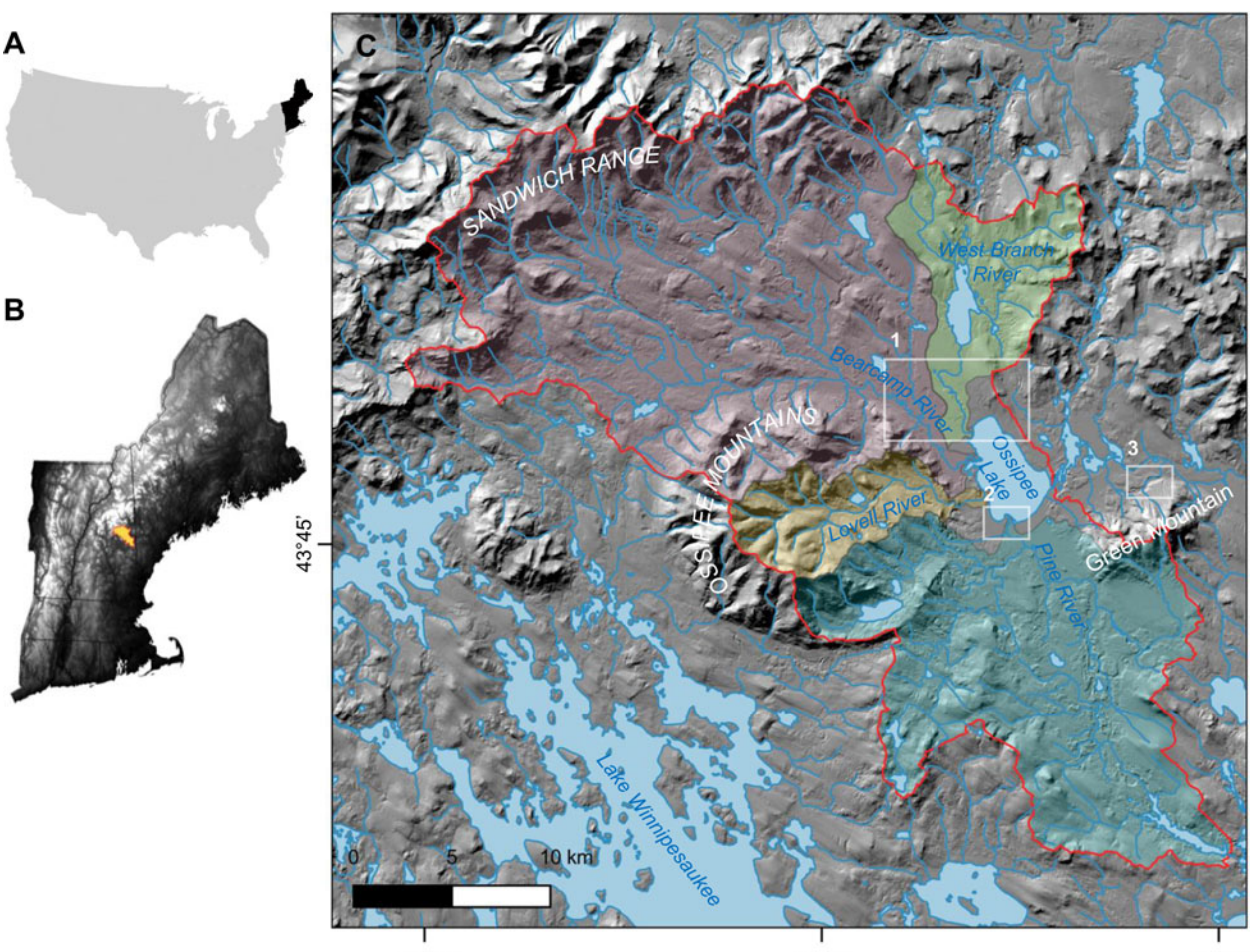

Figure 1. (A) Map of the conterminous United States highlighting the New England region. (B) Simplified elevation map of the New England region indicating the location of the Ossipee Lake watershed. (C) Shaded relief map of the Ossipee Lake watershed (outlined in red) and primary sub-drainage basins. Local elevation ranges from 124 m at Ossipee Lake to more than 1200 m at summits within the Sandwich Range. The Ossipee Mountains reach elevations of 900 m. Numbered rectangles indicate footprints of light detection and ranging (LIDAR) shaded relief maps shown in Fig. 2.

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well suited to investigations of Holocene landscape evolution. Numerous examples of incised stream channels and gullies, alluvial fans, and erosional scarps formed from channel and shoreline migration visible in light detection and ranging (LIDAR) digital elevation models (DEMs; Fig. 2) illustrate the extent of postglacial sediment redistribution within the region. The dominantly sandy shoreline of the lake, prominent deltas at the mouths of the four primary tributaries entering Ossipee Lake (Bearcamp, Lovell, Pine, West Branch; Figs. 1–3), and postglacial migration of the lake outlet in response to beach processes and long-shore currents (Newton, 1974b) further illustrate the abundance of available sediment and its ongoing redistribution within the watershed.

Ossipee Lake has a surface area of 13 km^2, average depth of 8.5 m, and maximum depth of 19.5 m (Fig. 3). The lake's volume and depth aid in trapping sediment from inflowing streams, and its simple bowl-shaped geometry likely simplifies transport and depositional patterns within the lake. The large catchment area of the Ossipee watershed relative to the lake's surface area further helps concentrate the deposition of sediment and maximize the signal from terrestrial sediment input.

Human occupation of the Ossipee watershed likely spans much of the Holocene, though regional estimates of the indigenous population in New England are relatively low for much of the postglacial period, with peaks occurring during the Middle and Late Holocene (Munoz et al., 2010). Population rose during the Late Archaic (6–3 ka) and Late Woodland (1–0.5 ka) intervals. The latter peak has been attributed to the regional emergence of horticulture of native species and cultigens, especially maize.

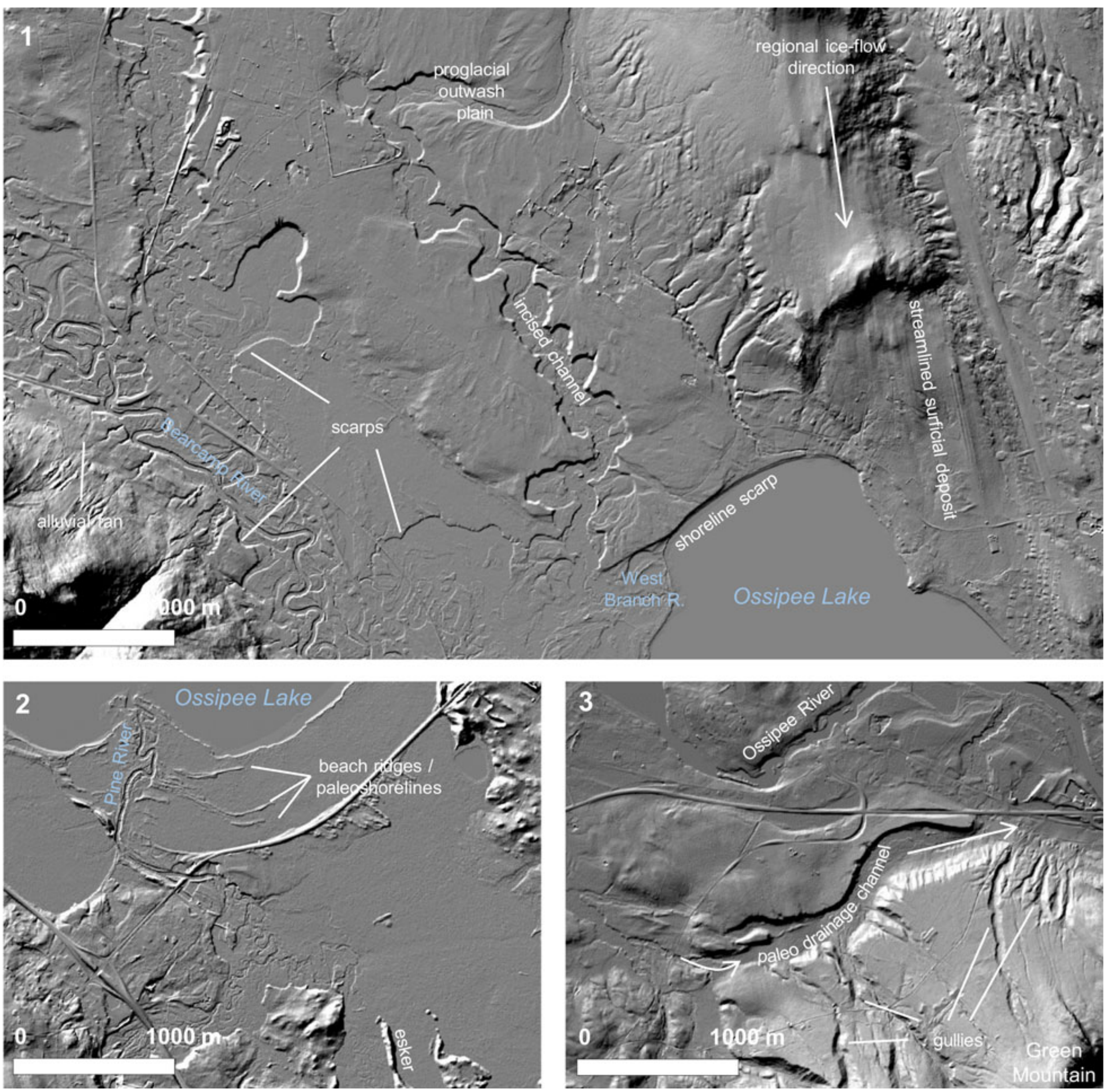

Figure 2. Light detection and ranging (LIDAR) shaded relief maps showing landscape features in the vicinity of Ossipee Lake. Locations of numbered panels are indicated on watershed map included in Fig. 1C. Labeled features highlight the abundance of unconsolidated sediment comprising surficial deposits within the Ossipee Lake watershed and emphasize postglacial transport and erosion of sediment within the region.

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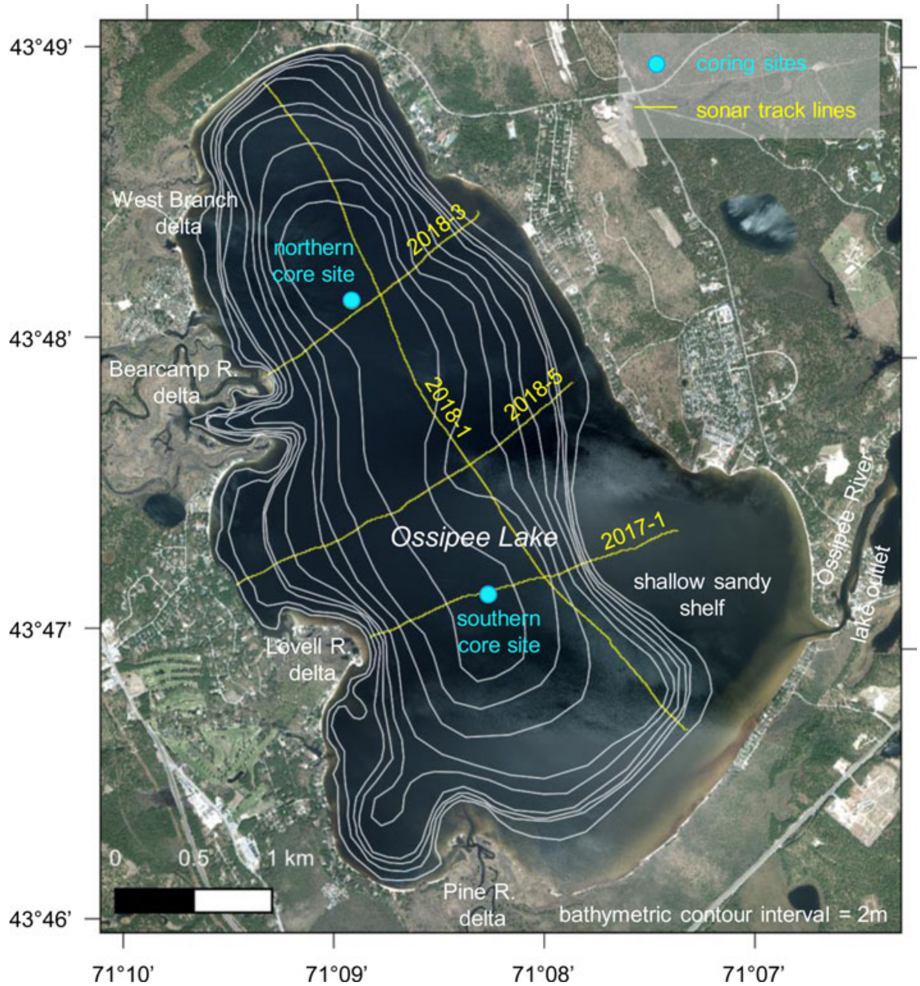

Figure 3. Bathymetric map of Ossipee Lake overlaid on 2015 orthoimagery (30 cm resolution). Also shown are sediment core locations, subbottom sonar track lines, major tributaries to Ossipee Lake, and the prominent shallow shelf in the southeastern corner of the lake (modified from LeNoir, 2019). The greatest depth is located at the northern coring site.

However, archaeological data suggest a minimal role for horticulture before the arrival of Europeans (Chilton, 2010). At the time of European arrival to the region in the mid-seventeenth century, the main village of the Ossipee tribe was located on the western shore of Ossipee Lake, with the lake and its tributaries serving as an important travel conduit (Price, 2002). Euro-American settlement displaced the native population and resulted in widespread forest clearance, dam construction, and conversion of land to agriculture over the ensuing centuries. The town of Ossipee was incorporated in 1785 CE; population of the surrounding Carroll County first peaked in 1860 CE, with census data recording the presence of 2758 farms and 50% of the surveyed county being improved land (Merrill, 1889). The Industrial Revolution and western expansion of the United States in the late nineteenth century led to the abandonment of many New England farms and subsequent natural reforestation. While the present landscape remains dominantly forested, rural residential development throughout the twentieth and twenty-first centuries has led to increasing population, and commercial timber harvest has continued in isolated portions of the watershed.

METHODS

We carried out fieldwork at Ossipee Lake during June 2017 and June 2018. Subbottom sonar surveys were conducted using a SyQuest StrataBox HD single-frequency (10 kHz) instrument. Subbottom depths were approximated based on the known water depth and assumption of a constant speed of sound. Sediment cores were collected from both the northern (43°48.12′N, 71°9.00′W; 19.5 m water depth) and southern (43°47.16′N, 71°8.28′W; 17.7 m water depth) ends of the large central basin of the lake (Fig. 3). Short (~1 m) gravity cores were collected to ensure an intact sediment–water interface; transparent core tubes allowed field verification of undisturbed sediment overlain by clear water. A single ~2 m piston-percussion core was collected at the northern site. Two overlapping sequences of multiple 3 m drives were collected from the southern site using a Uwitec piston-percussion corer.

Sediment cores were split lengthwise, visually described, and photographed before further analyses were conducted. We used an ITRAX (Cox Analytical Systems; Croudace et al., 2006) core scanner housed in the Geosciences Department at the University of Massachusetts Amherst to obtain X-radiographs and measure bulk elemental abundances via scanning X-ray fluorescence (XRF) using a Mo X-ray source at 30 kV voltage and 55 mA current. Cores were scanned at 1.0 mm resolution with a count time of 10 s, except for the short surface cores, which were scanned using a 15 s count time. We limit our reporting of XRF results to a subset of elements that provide insight on terrestrial sediment input. Specifically, we report results for potassium, which has been shown to be a reliable indicator of clastic sediment input to northeastern lakes (Yellen et al., 2014; Cook et al., 2015, 2020), in addition to silicon and titanium. Silicon in lake sediment can be derived from both the input of terrestrial sediment and the accumulation of autochthonous silica of biogenic origin, with the ratio of silicon to titanium providing insight into variations in the relative proportion of biogenic silica that comprises the inorganic component of the sediment (Croudace et al., 2006; Brown, 2015). We note that the 10 s count time used for our XRF analyses provides poor detection limits for silicon (Brown, 2015), and thus we are limited to qualitative interpretation of these data. Magnetic susceptibility was measured using a Bartington MS2E sensor at 0.5 cm intervals using split-core logging methodology (Nowaczyk, 2001). Percent loss on ignition (LOI) and dry bulk density (ρ_{db}) were measured on 1 cm^3 subsamples removed from the cores at 1 cm intervals following standard procedures (Dean, 1974). Continuous composite sedimentary sequences for the north and south coring sites were constructed by correlating the visual stratigraphy and LOI, magnetic susceptibility, and XRF data from individual cores (Supplementary Figs. 1 and 2, Supplementary Table 1) and identifying portions from individual cores that could be spliced together into a single continuous sequence. Composite sequences totaled 2.31 m at the northern site and 8.63 m at the southern site.

Age constraints for the sedimentary sequence were obtained from a combination of ^{137}Cs and ^{210}Pb stratigraphy and radiocarbon dating of nine terrestrial macrofossils and two bulk sediment samples recovered from the cores (Table 1). The clear correlation among cores allowed age control points determined from individual cores to be readily placed on the composite depth scale (Supplementary Table 1). Radiocarbon dates were determined via accelerator mass spectrometry (AMS) at the National Ocean Sciences Accelerator Mass Spectrometry laboratory at Woods Hole Oceanographic Institute in Woods Hole, Massachusetts, and at Direct AMS in Bothell, Washington. Radiocarbon ages were calibrated to calendar years BP, where present corresponds to 1950 CE, utilizing the IntCal13 calibration curve (Reimer et al., 2013) and the open-source R package CLAM (Blaauw, 2010). One-centimeter-thick slices of sediment were dried, homogenized, and analyzed via gamma spectroscopy using a Canberra GL2020 R low-energy gamma detector to determine ^{137}Cs and ^{210}Pb activity profiles for the upper 35 cm of the southern core sequence. The onset (1954 CE) of detectable ^{137}Cs and subsequent peak (1963 CE) provided two additional age-control points used in the final construction of an age–depth model for the composite sequence. In addition, the open-source R package serac (Bruel and Sabatier, 2020) was used to evaluate the ^{210}Pb profile using both the constant rate of supply (CRS; Appleby and Oldfield, 1978) and constant flux constant sedimentation (CFCS; Krishnaswamy et al., 1971) models. Ultimately, the sedimentation rate determined via application of the CFCS model was used to estimate the age (1890 ±10 yr) of the first prominent stratigraphic horizon that could be correlated among all cores (at 33.5 cm depth in the southern composite sequence), providing one additional control point for the age–depth model.

We used the three control points established from the ^{137}Cs and ^{210}Pb stratigraphies along with 10 radiocarbon dates to construct a final age–depth model for the southern composite sequence. A variety of age–depth modeling methods were investigated, including various interpolation methods using "classical" techniques (Blaauw, 2010), Bayesian methods (Bacon; Blaauw and Christen, 2011), and incorporation of time-varying accumulation rates derived from variations in sediment composition (Minderhoud et al., 2016). The results of our examination of differing age–depth models are described in detail by LeNoir (2019) and demonstrate that the primary interpretation of results is not altered by choice of age–depth modeling technique, though all models have shortcomings. As described herein, we utilized the age–depth model derived from linear interpolation between control points defined by the 2-sigma uncertainty in the calibrated ages calculated in the R package CLAM (Blaauw, 2010) and note the following caveats. Linear interpolation in CLAM underestimates the uncertainty in the age of sediment at most depths, produces (potentially spurious) inflection points in accumulation rate at each control point, and is unable to account for changes in sedimentation rate between control points, resulting in underestimation of peak accumulation rates during short-duration events. Nonetheless, linear interpolation in CLAM reduces subjective decision making around input parameters found in other models, and its shortcomings are predictable and can therefore be taken into consideration during interpretation of results.

We examined changes in the mass accumulation rate of clastic sediment ($MAR_{clastic}$) in Ossipee Lake as a proxy for suspended sediment yield (SSY) from the watershed using a similar approach to Cook et al. (2020). $MAR_{clastic}$ per unit area of lake bottom ($g/cm^2/yr$) was determined using the equation:

$$MAR_{clastic} = SR \times \frac{\rho_{db}(100 - LOI)}{100} \qquad (Eq.1)$$

where SR is the instantaneous bulk sedimentation rate (cm/yr) defined by the slope of the age–depth model and ρ_{db} and LOI are the dry bulk density (g/cm^3) and percent mass loss on ignition, respectively, at corresponding depths. Estimates of SSY in $Mg/yr/km^2$ were derived from $MAR_{clastic}$ using the equation:

$$SSY = MAR_{clastic} \times \frac{LA}{CA} \times 10,000\ Mg/\ g/cm^2/km^2 \qquad (Eq.2)$$

where LA and CA are the lake area and catchment area, respectively. Rather than using the total surface area of the lake, we based LA on the area of the lake below the 8 m depth contour (7.5 km^2), the area within which the majority of Holocene sediment infill is observed based on interpretation of the subbottom sonar transects (Fig. 4).

RESULTS

Subbottom sonar results from three W-E transects and a single N-S axial transect reveal more than 20 m of stratified deposits beneath Ossipee Lake (Fig. 4). Despite poor penetration in portions of the lake, likely due to gas present in the sediment, continuous, nearly horizontal acoustic reflections can be traced across large portions of the lake subbottom. The most prominent feature, identifiable in all subbottom sections, is a transition to stronger reflections at approximately 6 m below lake bottom (identified by the dashed green line in Fig. 4). The unit above this horizon tapers toward the lake margins and is generally limited to areas of the lake below ∼8 m water depth. This unit is identified as the Holocene lake fill based on sedimentary and chronological evidence. The unit below this, characterized by prominent reflections, is interpreted as late-glacial lake sediment. An additional depositional unit in the southeastern portion of the lake is visible in transect 2017-1 (Fig. 4D), bounded above by the flat, shallow

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Table 1. Radiocarbon sample information from the north and south composite core sequences, including all possible calibrated age ranges and their probabilities based on the 95% confidence intervals of the radiocarbon ages.

Lab ID	Material	Core section	Basin	Section depth (cm)	Composite depth (cm)	^{14}C age	^{14}C error	Calendar yr BP range	Probability
OS-137263	Plant/wood	17-2-1	South	72.5	72.5	500	15	537–512	95
OS-137545	Plant/wood	17-2-2	South	31	127	1030	45	814–800 866–826 1012–901 1056–1020	2.5 8.3 74.5 9.6
OS-137303	Plant/wood	17-2-2	South	67	163	1290	15	1209–1182 1280–1228	36.6 58.3
D-AMS 029666	Leaf fragment	18-2-1-2	South	37	237	2043	39	1911–1902 2116–1922	1.9 93
D-AMS 029667	Pine needle	18-2-1-2	South	129	329	3069	29	3186–3185 3362–3209	03 94.7
D-AMS 029664	Twig	18-1-2-1	South	83.5	371.5	3574	33	3745–3730 3791–3768 3974–3825	2.4 4 88.6
D-AMS 031773	Bulk sediment	18-2-2-1	South	84	457	5278	50	6185–5933	95
D-AMS 029669	Pine needle	18-2-2-2	South	34	546	6450	38	7299–7293 7430–7301	1.4 93.4
D-AMS 029665	Leaf fragments	18-1-3-1	South	21	595	7804	51	8721–8446	95
D-AMS 031772	Bulk sediment	18-1-3-1	South	106	680	10,129	48	11,431–11,410 11,484–11,479 11,551–11,493 12,020–11,600	1.2 0.3 3.9 89.6
D-AMS 029670	Pine needle	18-3-2	North	44	181	2208	40	2329–2133	95

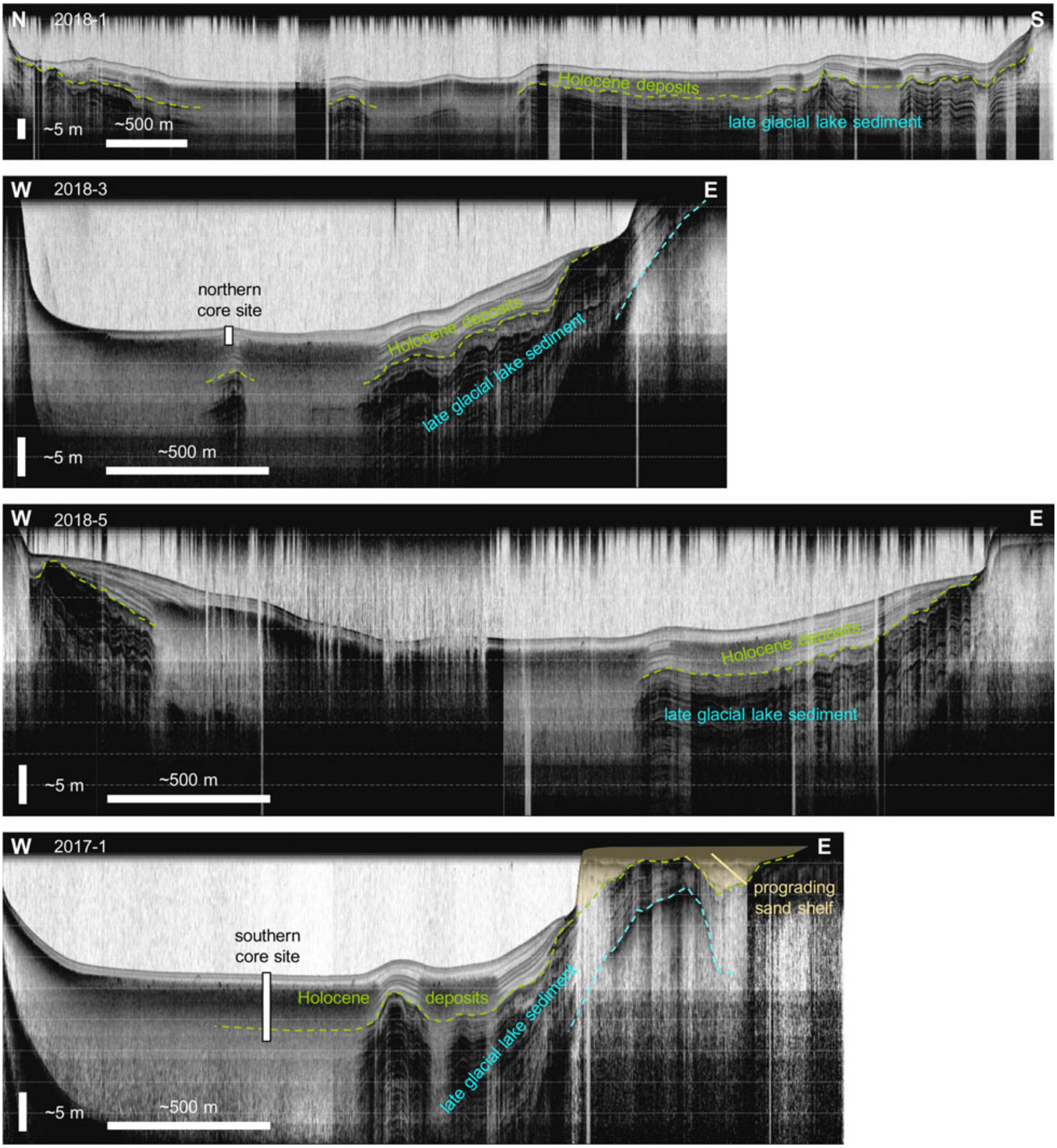

Figure 4. Subbottom sonar cross sections. Similar vertical exaggeration applied to all cross sections. Labels correspond to track lines shown on the bathymetric map in Fig. 3. Approximate location of coring sites indicated on transects 2018-3 and 2017-1. Basal contacts of Holocene lake fill and proglacial lake sediments are identified along with a prograding sand body in the southeastern corner of the lake (transect 2017-1; modified from LeNoir, 2019).

lake bottom in this portion of the lake and bounded below by the stratified late-glacial sediments. This unit appears nonconforming with the underlying late-glacial sediments and distinct from the Holocene lake fill. Field observations indicated that surface sediment in this shallow, southeastern portion of the lake are dominantly composed of sand.

The lowermost sediment recovered from the southern basin, from 8.63 m to 6.90 m composite depth below lake bottom, is light gray in color and composed of diffuse silt and clay laminae with occasional black streaks (Fig. 5B). Organic content is low (LOI < 4.26%), ρ_{db} varies from 0.82 to 1.09 g/cm^3, and magnetic susceptibility ranges from 17.08 to 191.24×10^{-5} standard international units (SI) (Fig. 6). From 6.90 m to ~6.18 m, the organic content of the sediment progressively increases as ρ_{db}, magnetic susceptibility, and potassium content all decrease (Fig. 6). The depth of this transition from dense, inorganic sediment to lower-density, more organic-rich sediments is consistent with the prominent transition observed in the subbottom sonar at ~6 m below lake bottom, where more acoustically transparent material overlies a sequence of stronger reflections (Fig. 4).

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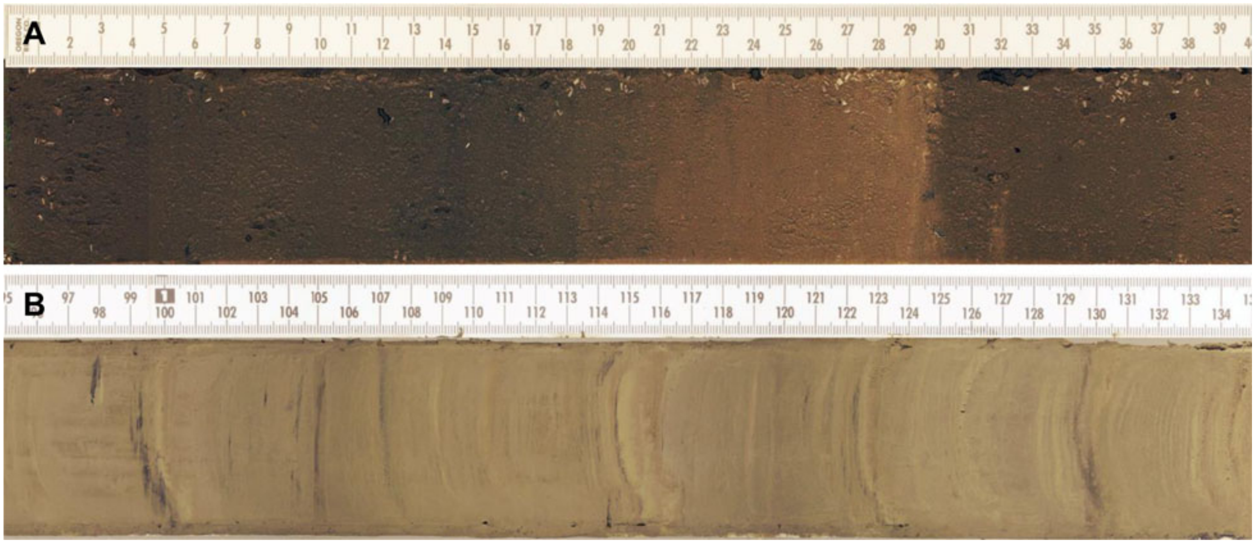

Figure 5. Split-core photographs depicting (A) typical Holocene sediment interrupted by a prominent, clastic event deposit and (B) proglacial lake sediment at the base of the recovered sequence. In both panels the core top is oriented to the left.

The upper ~6.18 m of the southern composite core and the entire 2.31 m northern core sequence are composed primarily of dark brown, moderately organic (15–25% LOI), fine-grained (silty) sediment with a ρ_{db} ranging from 0.17 to 0.46 g/cm^3 and magnetic susceptibility values ranging from 1.93 to 64.21×10^{-5} SI (Figs. 5A and 6). Throughout the record, silicon and titanium covary and are strongly correlated ($r^2 = 0.82$; Supplementary Fig. 3). The abundance of both elements broadly follows a similar pattern to LOI, magnetic susceptibility, and potassium (Fig. 6, Supplementary Fig. 3) and generally decrease from the earliest to latest periods of the record. The ratio of silicon to titanium decreases slightly over the course of the record, though low abundances of silicon above ~2.6 m were near or below the detection limit for the XRF instrument (as evident from occasional zero values for peak area counts) and likely result in spuriously low Si:Ti values for the portion of the record above 2.6 m.

Dispersed intervals of lighter-brown sediment occur throughout the upper 6.18 m portion of the southern core. These intervals are enriched in clastic (minerogenic) sediment, as evident from a decrease in organic content (LOI excursions are 5–10% below that of underlying sediment) and increases in density, magnetic susceptibility, and potassium content (Figs. 5 and 6). These units are further characterized by sharp basal contacts that result in rapid excursions of proxy measurements that gradually return toward prior values, indicating compositional grading. We term these intervals "event deposits." A total of 19 event deposits were identified in the southern composite sequence (Fig. 6). The uppermost event deposit, beginning at 33.5 cm depth in the southern core and pictured in Figure 5A, is correlative among all cores we collected at both the southern and northern sites, also correlative are five underlying event deposits within the overlapping portion of the northern and southern records (LeNoir, 2019; Supplementary Fig. 2). This uppermost event deposit was previously identified in multiple Ossipee Lake cores collected by Perello (2015), further demonstrating its widespread continuity. While we did not perform particle-size analysis, data from Perello (2015) indicate a slight decrease in median particle size from ~18 µm to 12 µm (dominated by an increase in clay content) at the base of the unit, followed by a gradual, but highly variable return above. Correlation of the event layers across the deep basin of the lake along with the continuous, parallel nature of reflections in the subbottom sonar data suggest widespread continuity of the sedimentary sequence in the central basin of Ossipee Lake.

The combined results of the ^{137}Cs and ^{210}Pb stratigraphy and 10 ^{14}C ages from the southern composite sequence constrain the age–depth relationship of the sediment from ~12,000 cal yr BP to the collection date of the cores in 2017 CE (Fig. 7). The onset and subsequent peak of detectable ^{137}Cs at 14.5 cm and 11.5 cm, respectively, are in close agreement with the estimated ages of the sediment determined from both CRS and CFCS models of ^{210}Pb accumulation (Fig. 7). Below 25 cm, the CRS and CFCS age models diverge considerably. While the constant accumulation rate of the CFCS model is likely unrealistic, the marked decrease in accumulation rate below 25 cm implied by the CRS model is inconsistent with the core stratigraphy, which includes a prominent event deposit beginning at 30 cm in core 17-1 (composite depth of 33.5 cm; Fig. 5A). We suspect that the most likely origin of the event deposit was increased deposition of clastic sediment, such that an age model requiring reduced accumulation through this interval is unrealistic. Consequently, we estimated the basal age of this event deposit from the CFCS age model as 1890 CE (acknowledging that the actual timing may be even younger) and incorporated this point in the age–depth model of the composite sequence. Over the 6.8 m interval of the composite sequence bracketed by age constraints (11,810 ± 210 cal yr BP to 2017 CE), the average linear accumulation rate is 0.06 cm/yr, with increased rates occurring after ~4000 cal yr BP and after ~1900 CE.

The accumulation rate of clastic sediment ($MAR_{clastic}$; Fig. 8) varies throughout the record in accordance with changes in the slope of the age–depth model (Fig. 7) and variations in the density (ρ_{db}) and composition (% LOI) of the sediment (Fig. 6). Given evidence in the subbottom sonar data for the accumulation of at least 15 m of sediment between deglaciation (circa 14,500 cal yr BP; Ridge et al., 2001, 2012; Dalton et al., 2020; Ridge, 2022) and the transition to Holocene lake deposits, accumulation rates must have been at least 0.6 cm/yr from 14,500 to 12,000 cal yr BP, yielding

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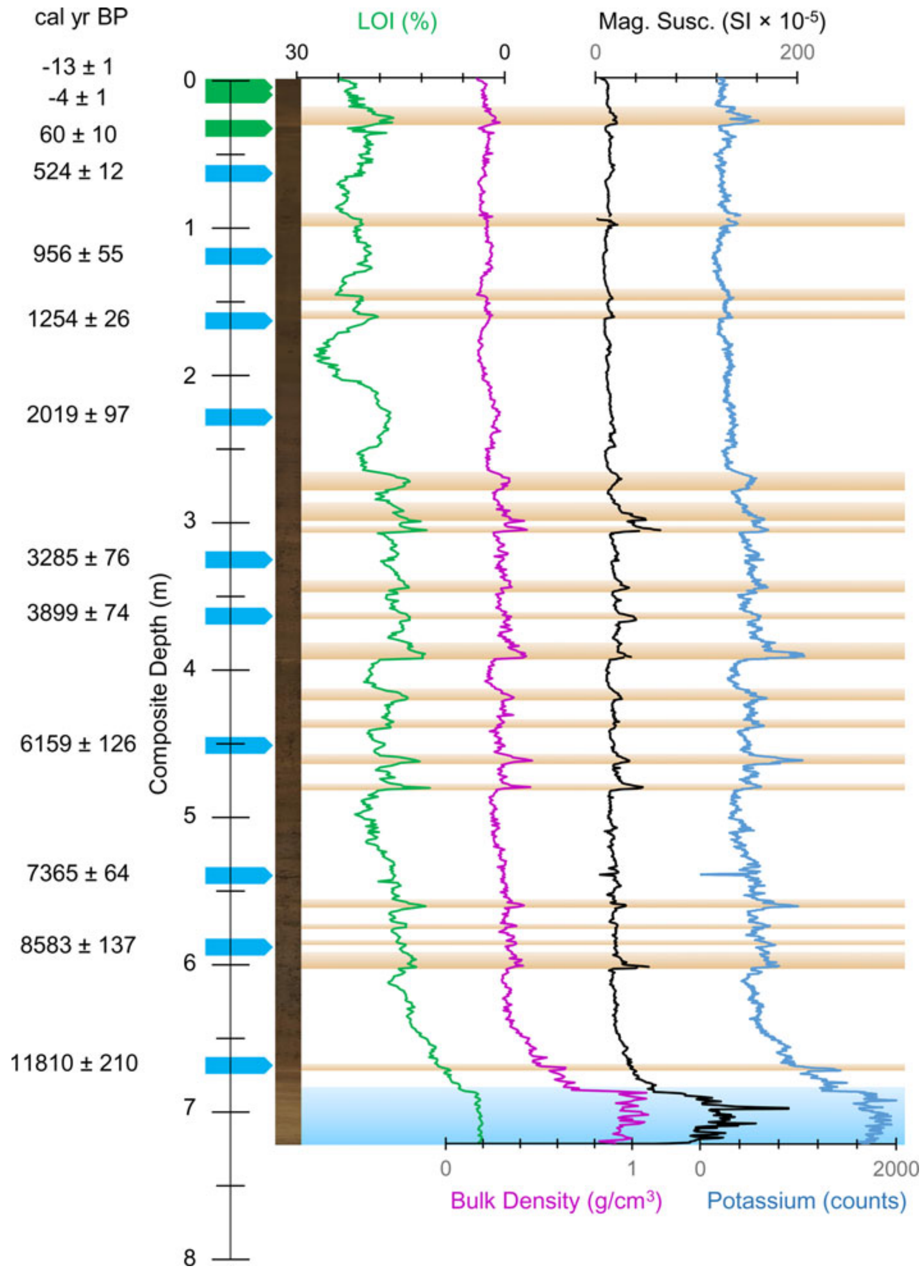

Figure 6. Core data from the southern composite sequence from Ossipee Lake. Analytical results span the upper 7.25 m. An additional 1.38 m of core was recovered and described, but not analyzed. Blue arrows indicate the position of radiocarbon dates; green arrows indicate control points derived from ^{137}Cs and ^{210}Pb profiles. Event layers (tan bands) are identified as intervals of decreased organic content (high LOI) and increased elevated minerogenic content (elevated ρ_{db}, magnetic susceptibility, and potassium). The portion shaded blue is interpreted as late-glacial deposits (modified from LeNoir, 2019).

$MAR_{clastic}$ values higher than anything observed during the Holocene. From 11,810 to 9,000 cal yr BP $MAR_{clastic}$ decreases from ~0.16 g/cm^2/yr to 0.07 g/cm^2/yr in response to a decrease in the input of clastic sediment evident from the increasing LOI over this interval. From ~9000 cal yr BP to 1890 CE, $MAR_{clastic}$ varies widely from 0.07 g/cm^2/yr to 0.28 g/cm^2/yr, with the highest rates associated with distinct event deposits. Average $MAR_{clastic}$ is 0.014 g/cm^2/yr, yielding an estimated SSY from the watershed of 1.4 Mg/yr/km^2. A slightly increasing trend in $MAR_{clastic}$ of 0.002 g/cm^2/1000 yr is evident over this interval ($r^2 = 0.24$, P value = 0.18; Fig. 8). The highest calculated $MAR_{clastic}$ values are observed after 1850 CE and are dominated by the presence of the prominent event deposit at 33.5 cm composite depth (Fig. 5A). Peak $MAR_{clastic}$ is 0.072 g/cm^2/yr and averages 0.035 g/cm^2/yr from 1850 to 2017 CE, corresponding to a watershed SSY of 7.2 Mg/yr/km2 and 3.5 Mg/yr/km^2, respectively. While $MAR_{clastic}$ since 1850 CE appears anomalous compared with the rest of the record, we note that this is the only portion of the record with centennial-scale age control. Given that the uppermost event deposit is unremarkable in terms of its density, LOI, or other indicators of composition, it is likely that actual peaks in $MAR_{clastic}$ in the earlier portion of the record would equal or exceed the values observed after1850 CE if deposition times could be constrained over similarly short intervals in the past.

DISCUSSION

Our radiocarbon chronology indicates that the southern composite core sequence from Ossipee Lake spans the entire Holocene and includes ~1.7 m of clastic-rich gray sediment that we

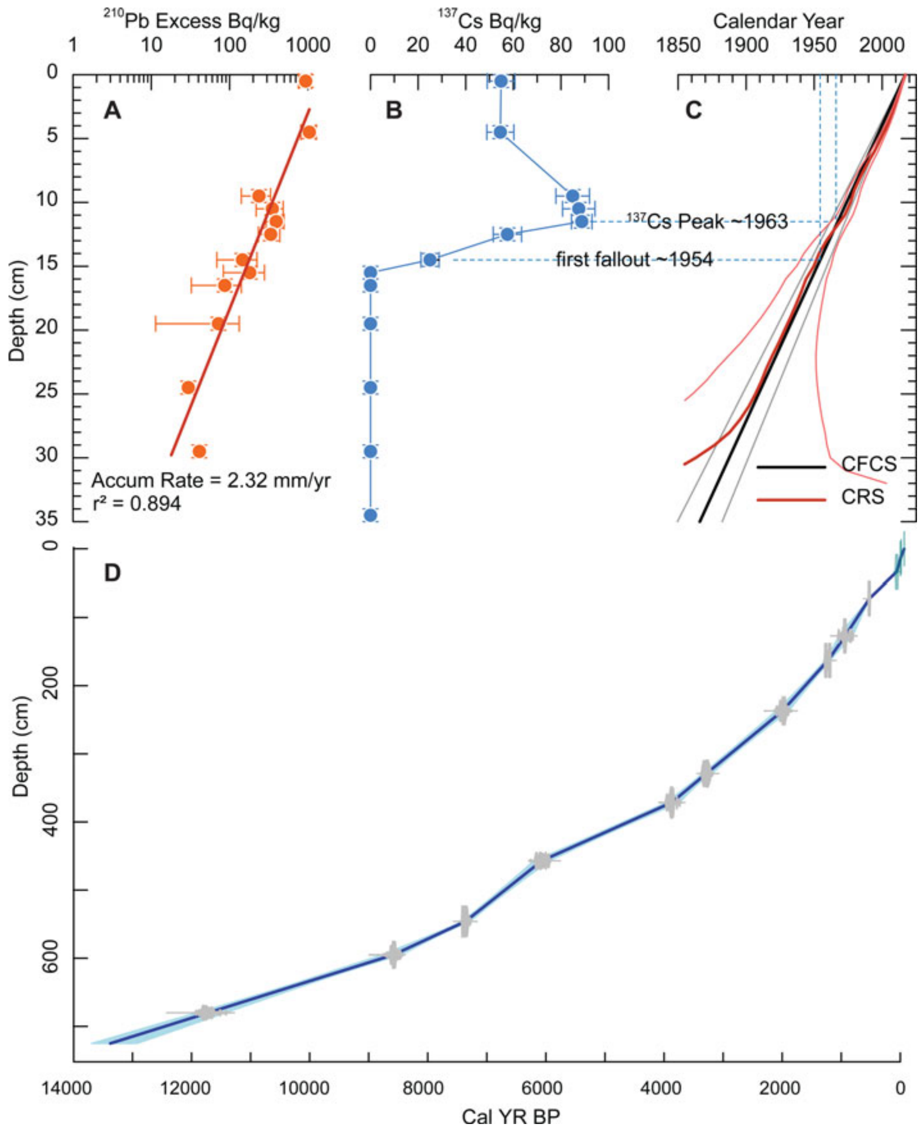

Figure 7. Age–depth constraints for the southern composite sequence from (A) ^{210}Pb activity profile and (B) ^{137}Cs activity profile identifying first detected fallout ca. 1954 CE and peak fallout ca. 1963 CE. (C) Constant rate of supply (CRS) and constant flux constant sedimentation (CFCS) age–depth models as derived from the ^{210}Pb profile in A. (D) Age–depth model for the full composite sequence based on linear interpolation between radiocarbon age constraints (in gray) and ^{210}Pb and ^{137}Cs constraints as described in the text (modified from LeNoir, 2019).

interpret to be late glacial in origin (Figs. 5 and 6). This allows us to consider paraglacial landscape evolution, as indicated by variability in the patterns of $MAR_{clastic}$ (Fig. 8), during the entire Holocene and through the period of Euro-American land-use change. Strong covariance among LOI, magnetic susceptibility, potassium, silicon, and titanium (Fig 6; Supplementary Fig. 3) supports our interpretation of variations in $MAR_{clastic}$ as primarily reflecting changes in terrestrial sediment input. However, we acknowledge that interpreting terrestrial processes from limited cores is fraught with uncertainty (e.g., Davis and Ford, 1982). Nonetheless, there are several lines of evidence supporting the interpretation of our Ossipee Lake sequence in terms of landscape evolution. First, the lateral continuity of strata identified in the subbottom data (Fig. 4) and between our northern and southern core sites (LeNoir, 2019; Supplementary Figs. 1 and 2) suggests that depositional patterns within the deep basin are spatially consistent. Second, the relatively large size of Ossipee Lake and the position of our coring sites away from active deltas lead us to believe that we are sampling fine-grained sediment delivered primarily in suspension by the inflowing rivers. Delivery of sediment to these distal locations is likely dominated by prevailing westerly winds and flow of water from tributaries on the western side of the lake to the outlet in the eastern corner of the lake. This is in contrast to more marginal locations in the lake subject to slope processes and more sensitive to delta migration. Finally, subbottom sonar data reveal that the present-day bathymetry characterized by a broad, flat central basin mimics the underlying surface, marking the boundary between late-glacial and Holocene deposits, which are nearly constant in thickness in the central portion of the lake (Fig. 4). Consequently, Holocene infilling of the lake from a maximum water depth of ~25 m to the present 19.5 m water depth is unlikely to have resulted in widely shifting depocenters or trapping efficiencies. While we cannot definitively rule out the possible influence of long-term delta progradation on $MAR_{clastic}$, we emphasize the distal setting of our coring sites and the fact that the package of Holocene sediment visible in the

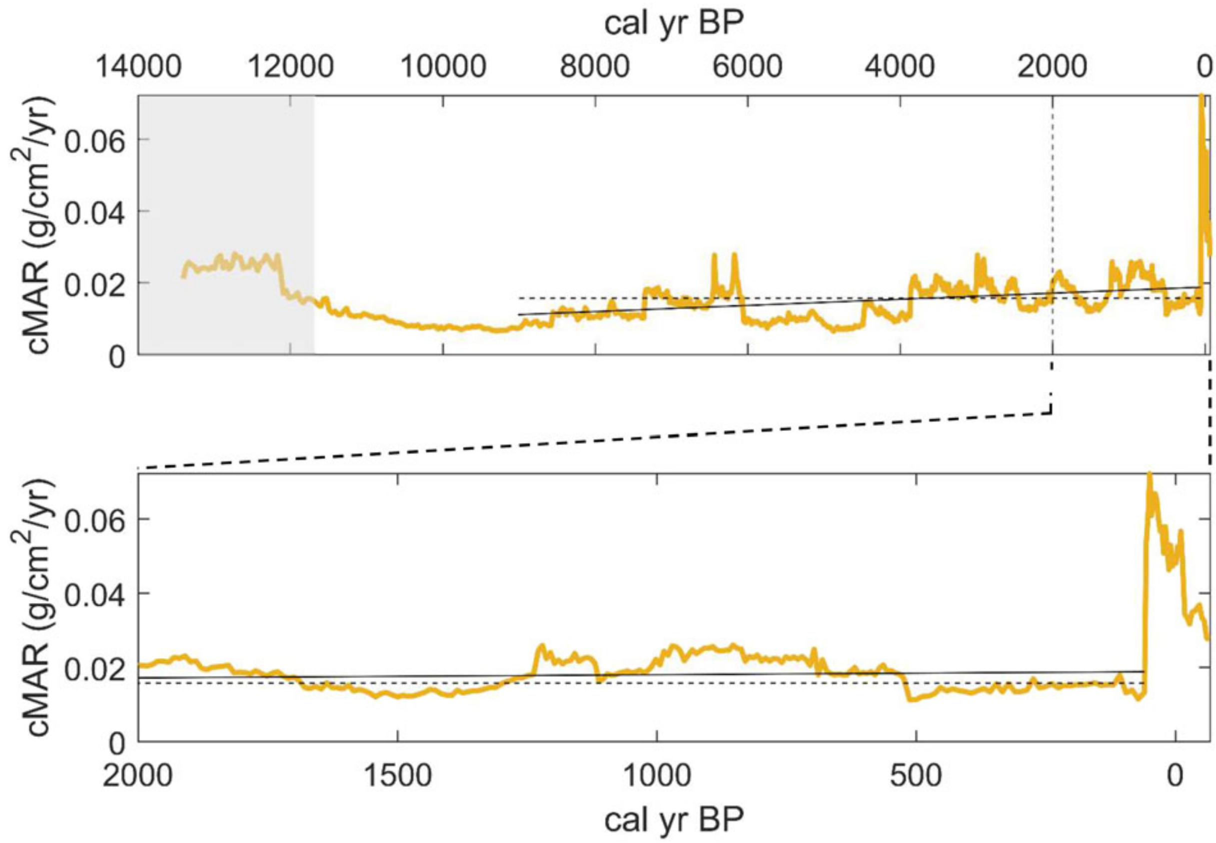

Figure 8. $MAR_{clastic}$ for the entire composite sequence (top) and last 2000 yr (bottom). Dotted line represents the mean from 9012 cal yr BP to AD 1890. Solid line depicts the slightly increasing trend in $MAR_{clastic}$ of 0.002 g/cm^2/1000 yr over this same interval ($r^2 = 0.24$, P value = 0.18). The gray box from 1180 cal yr BP to the end of the record highlights the portion of the record beyond the bottommost age control point, where accumulation rate in the age–depth model is assumed to be the same as the section above it. Elevated $MAR_{clastic}$ in this portion of the record is a function of denser sediment (modified from LeNoir, 2019).

subbottom data reveals no apparent thinning to the south or east as might be expected if proximity to primary deltas played a major role in determining accumulation rates. Consequently, the discussion that follows is based on the assumption that changes in $MAR_{clastic}$ predominantly reflect changes in the terrestrial suspended sediment delivered to Ossipee Lake from its watershed.

Late-glacial landscape evolution

The initial period of elevated $MAR_{clastic}$ followed by the transition from dominantly minerogenic to more organic-rich sediment and accompanying decline in $MAR_{clastic}$ from the earliest part of our record to ∼9200 ± 200 cal yr BP (Fig. 9) reflects the most pronounced interval of paraglacial landscape adjustment in the Ossipee watershed. The thickness of the pre-Holocene deposits evident in our subbottom data (Fig. 4) necessitate a >0.6 cm/yr linear sedimentation rate over some portion of 14,500 to 12,000 cal yr BP, as constrained by our lowermost radiocarbon date and the timing of regional deglaciation. This rate is roughly an order of magnitude higher than the mean sedimentation rate over the Holocene. Extremely high accumulation rates in proglacial settings are common (Desloges and Gilbert, 1991; Gilbert and Desloges, 1992) and are consistent with readily available surface deposits on the freshly deglaciated landscape, abundant meltwater for transporting sediment, and a lack of vegetation to help stabilize surface deposits. Consequently, it is likely that much of the pre-Holocene sediments were deposited in a proglacial setting, immediately following ice retreat.

The continuation of elevated $MAR_{clastic}$ even after the regional ice margin had retreated beyond the watershed boundary reflects ongoing paraglacial adjustments, likely including a pronounced period of stream incision driven by a combination of lake-level reduction, vegetation establishment, and glacial isostatic adjustments. Evidence for a higher lake level early in the deglaciation of the Ossipee Valley is provided by elevated shoreline features and paleo-drainage channels near the present lake outlet (Newton, 1974a, 1974b; Fig. 2). We see no sedimentological evidence of a lake-level reduction event within the core sequence that we collected and surmise that paleolake drainage likely occurred shortly after deglaciation (ca. 14,500 cal yr BP; Ridge et al., 2012) and no later than 11,810 ± 210 cal yr BP, the age of our lowest radiocarbon date. The Saco River valley, the next major drainage to the north of Ossipee Lake, was occupied by a series of small glacial lakes collectively referred to as Lake Pigwacket (Thompson, 1999), thought to have drained between 12,170 and 11,630 cal yr BP (Shuman et al., 2005). Falling lake level of an enlarged postglacial Ossipee Lake would not have isolated the lake basin from the dominant drainage networks supplying sediment to the lake. In contrast, lake-level reduction would have decreased the regional base level, initiated the widespread fluvial incision and gullying prevalent throughout the watershed (Fig. 2), and consequently increased sediment delivery to the lake, as evident from elevated $MAR_{clastic}$ in Figures 8 and 9. Pollen data from Echo Lake, located 30 km north of Ossipee Lake, are dominated by spruce (*Picea*) before 13,000 cal

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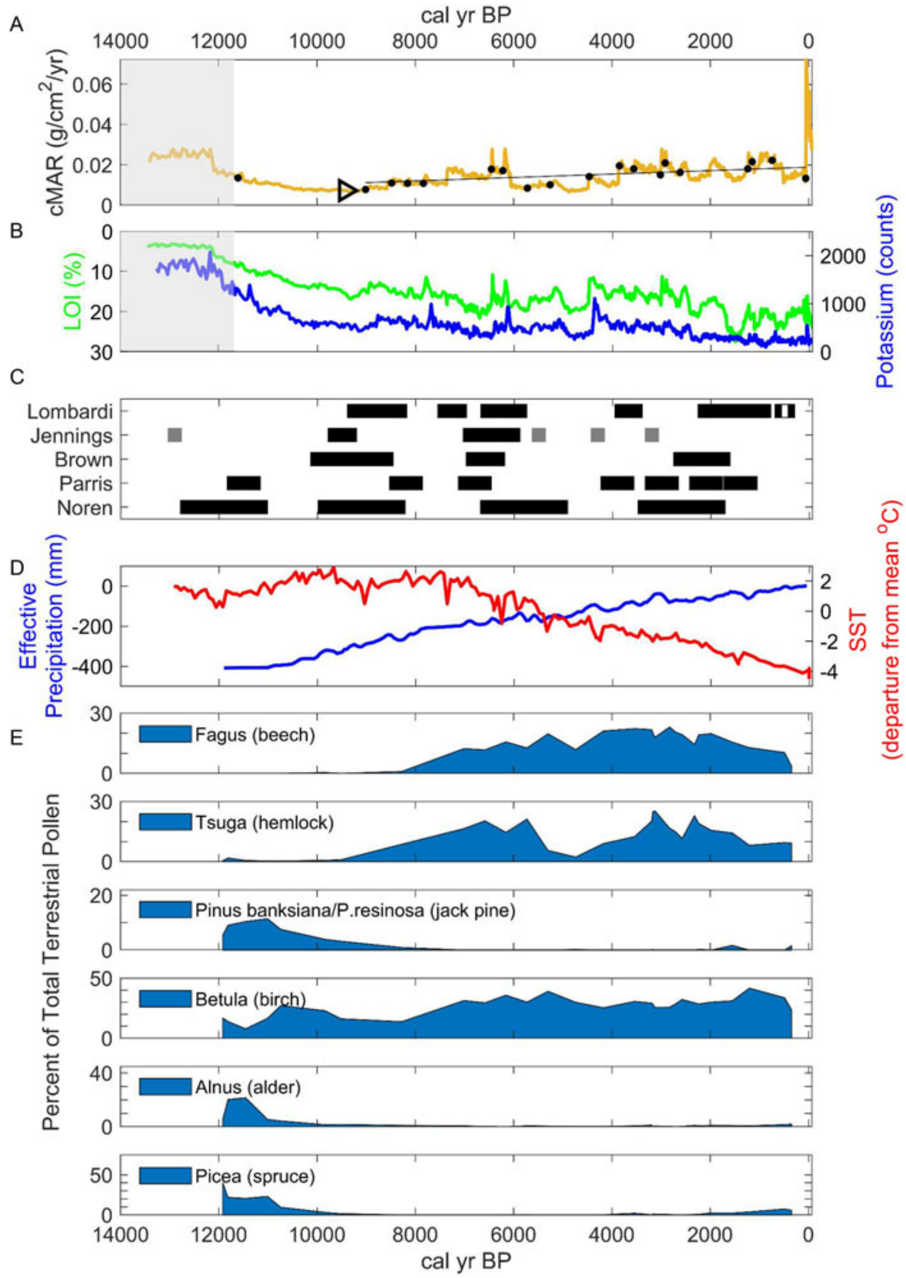

Figure 9. (A) Ossipee lake record of $MAR_{clastic}$ and (B) LOI and potassium compared with regional records of environmental change, including (C) intervals of terrestrial sediment redistribution as recorded in lakes (Brown et al., 2002; Noren et al., 2002; Parris et al., 2010), alluvial fans (Jennings et al., 2003), and floodplains (Lombardi et al., 2020); (D) regional climate reconstructions (Shuman and Marsicek, 2016; Sachs, 2007); and (E) regional vegetation history (Shuman et al., 2005; figure modified from LeNoir, 2019).

yr BP, transitioning through boreal taxa such as alder (*Alnus*), fir (*Abies*), and birch (*Betula*), before becoming dominated by haploxylon pine and oak (*Quercus*) by 11,000 cal yr BP (Shuman et al., 2005; Fig. 9E). These data reveal the establishment and evolution of the regional forest cover, which would have helped stabilize hillslopes, strengthen stream banks, and promote a transition from braided to meandering planforms as stream channels incised to the base level of the modern lake (Newton, 1974a, 1974b; Moore and Medalie, 1995; Fig. 2). In addition, differential rebound of 0.9 m/km resulting from retreat of the Laurentide Ice Sheet (Hooke and Ridge, 2016) would have steepened the gradients of south-flowing streams, including the Bearcamp River, the largest tributary to Ossipee Lake, which drains the highest elevation and steepest portions of the watershed. Therefore, lake-level reduction, vegetation establishment, and isostatic adjustments may have all contributed to fluvial incision. The decrease in $MAR_{clastic}$ beginning ~12,000 cal yr BP (Figs. 8 and 9) suggests that channel profiles may have begun stabilizing by this time, a pattern that is consistent with a period of most active fluvial incision in the earliest Holocene observed in the Missisquoi River valley in northern Vermont (Brakenridge et al., 1988) and the Connecticut River valley in southern New England (Schenck, 2018).

Early Holocene landscape changes

We interpret the interval of decreasing $MAR_{clastic}$ from ∼12,000 to 9000 cal yr BP (Figs. 8A and 9A) as reflecting the waning influence of the prior glacial conditioning of the landscape. During this interval, stream channel profiles likely approached equilibrium with the base level defined by the modern elevation of Ossipee Lake, the most readily erodible surface deposits were being exhausted, and the regional vegetation transitioned from boreal taxa to a forest dominated by oak (*Quercus*), beech (*Fagus*), birch (*Betula*), and hemlock (*Tsuga*) that persisted through the remainder of the Holocene (Shuman et al., 2005; Fig. 9E). Our inferred timing for stabilization of the landscape surrounding Ossipee Lake, ∼9200 ± 200 cal yr BP, aligns with the establishment of maximum vegetation coverage within the Mirror Lake, New Hampshire, watershed around 9500 to 9000 cal yr BP (Likens and Davis, 1975). The >5 ka time interval from deglaciation to apparent landscape stabilization around 9200 cal yr BP is consistent with the extended timescales of paraglacial sediment reworking demonstrated for glaciated British Columbia river basins (Church and Slaymaker, 1989). The shape of the Ossipee Lake $MAR_{clastic}$ curve during this interval is consistent with an exhaustion model of paraglacial landscape evolution (Ballantyne, 2002), in which the supply of easily mobilized sediment decreases as the landscape stabilizes. However, lacking the detailed age control within this interval needed to adequately constrain short-duration variations in sediment yield, we cannot rule out an evolution dominated by waves of erosion, as suggested by Church and Ryder (1972). Notably, the variable $MAR_{clastic}$ pattern and episodic occurrence of event deposits throughout the Holocene (Figs. 8A and 9A) suggest ongoing reworking of glaciogenic deposits throughout the study period.

Middle through Late Holocene landscape evolution

The Ossipee Lake record of $MAR_{clastic}$ from ∼9000 cal yr BP to ∼1850 CE is highly variable, but contains a slight trend toward increasing $MAR_{clastic}$ (Figs. 8A and 9A). Interestingly, the lowest values of $MAR_{clastic}$ during the entire record are observed around ∼9000 cal yr BP, corresponding to a period of increased fire activity in southern New England during what was broadly the warmest and driest interval of the Holocene (Oswald et al., 2020). While we cannot rule out short-duration increases in erosion and subsequent lake sedimentation in response to individual wildfires, the occurrence of the lowest $MAR_{clastic}$ values during the period of greatest regional fire activity suggests that on centennial or longer timescales, fire frequency is not a primary driver of erosion rates. In general, variations in $MAR_{clastic}$ reflect the combined influence of the sedimentation rate defined by the slope of the age–depth model and variations in the composition of the sediment. Though discrete peaks in $MAR_{clastic}$ are associated with the occurrence of event deposits (Fig. 9A) characterized by enriched minerogenic content (Fig. 9B), variations in the timing and frequency of event deposits are independent of millennial-scale changes in $MAR_{clastic}$ and the long-term increasing trend in $MAR_{clastic}$.

To further explore the origins of millennial-scale changes in $MAR_{clastic}$, we compiled existing Holocene-length records of terrestrial sedimentation in the northeastern United States (Fig. 9C) from lakes (Brown et al., 2002; Noren et al., 2002; Parris et al., 2010), alluvial fans (Jennings et al., 2003), and floodplains (Lombardi et al., 2020). Though these records reveal limited internal consistency, we note that the apparent periods of elevated terrestrial sediment redistribution in the regional records centered around ∼6500 cal yr BP and ∼2500 cal yr BP and separated by a multimillennial period of reduced activity are generally consistent with the pattern of $MAR_{clastic}$ in Ossipee Lake. In contrast, the long-term trend of increasing $MAR_{clastic}$ at Ossipee Lake is not observed in other regional records of terrestrial sedimentation. Both increasing $MAR_{clastic}$ over the Holocene and the episodic occurrence of event deposits (Figs. 8 and 9A) are contrary to simple exhaustion models of paraglacial sedimentation (e.g., Ballantyne, 2002) and instead reveal persistent or intermittent reworking of the landscape throughout the Holocene, as was observed in the Scottish Highlands by Ballantyne (2008).

While the increasing trend in $MAR_{clastic}$ over the Middle and Late Holocene is weak, the possibility that sediment export from the watershed was increasing, or even remaining constant, warrants further exploration, as sediment availability in this paraglacial landscape should theoretically have been decreasing (e.g., Ballantyne, 2002). An increase in biogenic silica production within the lake or its preservation in sediment over the course of the Holocene would impact our LOI-based determinations of the inorganic fraction of the sediment and subsequent calculations of $MAR_{clastic}$, yielding a spurious trend toward increasing $MAR_{clastic}$ over the same interval. However, strong covariance of silicon and other indicators of terrestrial sediment (Fig. 6, Supplementary Fig. 3) suggests that variations in the inorganic fraction of the sediment in Ossipee Lake are dominated by changes in terrestrial sediment input. Furthermore, a gradual decrease in Si:Ti over the Holocene is suggested by our XRF data, though we emphasize the qualitative nature of these results (Supplementary Fig. 3). This pattern could result from decreasing production of biogenic silica in the lake, decreased preservation in the sediment, or dilution of biogenic silica by increased input of silicon from terrestrial sources (Conley and Schelske, 2002). All of these possibilities are consistent with the observed increase in $MAR_{clastic}$ resulting from increased input of clastic sediment from the watershed rather than any increase in the amount of biogenic silica in the sediment.

Assuming that the apparent increasing trend in $MAR_{clastic}$ over the Middle and Late Holocene truly reflects changing delivery of sediment from the watershed, we explore several plausible mechanisms capable of driving changes in sediment yield from the surrounding landscape. Regional pollen records (Shuman et al., 2005; Oswald et al., 2020; Fig. 9E) reveal changes in vegetation throughout the Holocene; however, we see no obvious trend in vegetation that might lead to increasing sediment availability and a subsequent increase in $MAR_{clastic}$ in Ossipee Lake. The long history of human habitation in the Ossipee region and the potential for human modification of the landscape to have produced changes in sediment yield over at least the past several millennia (e.g., Dearing and Jones, 2003) provide another possible mechanism to explain the long-term trend in $MAR_{clastic}$. However, indigenous populations in the region reached maxima during the Late Archaic (5000–3000 cal yr BP) and Middle–Late Woodland (1500–500 cal yr BP) periods (Munoz et al., 2010), which is inconsistent with the timing of peak $MAR_{clastic}$ in Ossipee Lake. An additional mechanism that could account for the long-term increase in $MAR_{clastic}$ is glacial isostatic adjustments affecting river gradients, base level, and/or the position of drainage divides. A forebulge would have existed 150–200 km south of the Laurentide Ice Sheet margin (Hooke et al., 2017) and migrated north as ice retreated (Hooke and Ridge, 2016). In Maine, the forebulge migrated from the coast to the Moosehead Lake region

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between 12,200 and 9500 cal yr BP at a rate of ~67 m/yr (Balco et al., 1998). Combining this knowledge with constraints on the timing of ice margin positions in the vicinity of Ossipee Lake (Ridge et al., 2001, 2012; Dalton et al., 2020), the forebulge likely migrated through the region before 9000 cal yr BP, limiting the potential impact of isostatic adjustments on subsequent sediment delivery.

Finally, we hypothesize that the most likely origin of any long-term increase in $MAR_{clastic}$ is the concomitant long-term increase in effective precipitation that occurred during the Holocene in this region (Shuman and Marsicek, 2016; Fig. 9D). This relationship suggests that moisture balance serves as an important control on long-term watershed erosion rates and is consistent with other regional observations relating differences in the sediment yield from individual hydrologic events (Yellen et al., 2016) and centennial-scale variability in erosion (Cook et al., 2015) to changes in underlying moisture balance. Such an increase in sediment yield necessitates the continued availability of easily reworked sediment (evident from the abundance of glacigenic deposits blanketing the watershed) and is consistent with Church and Slaymaker's (1989) observation that rivers in British Columbia are still responding to the last glaciation.

Historic-era land-use impacts and the origin of event deposits

$MAR_{clastic}$ increases abruptly at ~1890 CE, with the highest accumulation rates of the entire record observed within the last century and a half (Fig. 8). The inferred SSY peak of 7.2 Mg/yr/km^2 and 1850–2017 CE mean of 3.5 Mg/yr/km^2 nonetheless remain low relative to some rates proposed for other forested watersheds in the eastern United States (Patric et al., 1984). And while the recent increase in sediment yield might be expected based on the history of Euro-American settlement and land-use change in the region, and is consistent with human impacts in other regions (e.g., Davis, 1976; Dearing et al., 1987; Heathcote et al., 2013), our attribution of the increase in $MAR_{clastic}$ in Ossipee Lake to human land-use change must be tempered. First, our age–depth model provides limited resolution for constraining calculations of $MAR_{clastic}$, and the abrupt increase in $MAR_{clastic}$ is partially an artifact of an inflection point in the age–depth model at the base of the uppermost event deposit. Nonetheless, the event deposit is characterized by increased clastic content and increased bulk density, such that an increase in $MAR_{clastic}$ would exist even if the sedimentation rate (SR) remained constant throughout this interval. However, the anomalous nature of recent $MAR_{clastic}$ would be less extreme relative to earlier event deposits if age control was continuously well resolved over the entire record.

A second important consideration when interpreting the recent increase in $MAR_{clastic}$ is the origin of the uppermost event deposit, the most prominent stratigraphic feature of the past 500 yr (Figs. 5 and 9A), as well as other event deposits throughout the record. We assigned an age of 1890 ± 10 CE to the base of this event, based on interpretation of our ^{210}Pb and ^{137}Cs profiles. If the increase in clastic content defining this feature was a consequence of Euro-American land-use change increasing sediment delivery to the lake, then the timing appears several decades late relative to the 1860 CE maximum in Carroll County population and associated agricultural activity (Merrill, 1889). Uncertainty in our age–depth model could facilitate shifting the onset of this event layer earlier. However, doing so would result in a decrease in the calculated sedimentation rate between the base of the event layer and the first observed fallout of ^{137}Cs in 1954 relative to the sedimentation rate between 1954 and the core top; an outcome deemed implausible given the pattern of clastic deposition over these intervals. Furthermore, the abrupt nature of the basal contact of the event deposit (Figs. 5 and 9B) suggests a near instantaneous transition in sedimentation; a pattern that is inconsistent with a gradual increase in deforestation and agricultural land use and contrasts with existing records of sedimentation that show a gradual increase in clastic input in response to human land-use change (e.g., Davis, 1976; Dearing et al., 1987; Francis and Foster, 2001; Heathcote et al., 2013) The abrupt nature of this and other event deposits suggests possible deposition from a sediment gravity flow (e.g., Gani, 2004), originating either subaqueously or triggered by events in the watershed. However, the fine particle size and absence of textural grading within the uppermost event deposit as reported by Perello (2015) is inconsistent with most deposits resulting from density flows (Gani, 2004). In contrast, the compositional grading from highly clastic to increasingly organic-rich sediment observed in all event deposits (Fig. 6) is similar to deposits observed in Amherst Lake, Vermont (Cook et al., 2015). In that setting, event deposits were linked to periods of elevated input of clastic sediment from the watershed initiated by extreme floods and followed by a period of decreasing clastic input as the landscape gradually recovered from the initial disturbance (Cook et al., 2015). Cook et al. (2015, 2020) were able to correlate distinct event deposits to landscape disturbances related to historical floods in Vermont and Maine, respectively. In contrast, we were unable to link the uppermost event deposit in Ossipee Lake to any known historical flood event or other landscape disturbance. Indeed, with only one event deposit having occurred within last 500 yr in Ossipee Lake, we found no clear signature of any historical flood events, forest fires, or other known disturbances in the record. While the origin of the event deposits remains enigmatic, we hypothesize that they reflect abrupt increases in erosion caused by the most extreme hydrologic events triggering landslides in the uplands and/or avulsions and other adjustments in the fluvial network closer to the lake and/or the stochastic interaction of a laterally migrating stream channel occasionally intersecting a new repository of erodible sediment.

Overall, the infrequent occurrence of event deposits, averaging only 1 per ~500 yr over the Holocene, and the apparently modest SSY over the past century portray a landscape only moderately sensitive to disturbances. In contrast to other watersheds, where both distinct floods (Cook et al., 2015, 2020) and changes in land use (Cook et al., 2020) are clearly recorded in lacustrine archives, Ossipee Lake and its watershed are considerably larger than those focused on by other studies in the region. Sediment entering a larger waterbody may be distributed over a larger area, potentially muting the depositional signature. The large area of the Ossipee watershed also provides more opportunity for trapping and storage of sediment in lakes, wetlands, and floodplains and behind dams upstream of the lake. The Amherst Lake and Little Kennebago Lake watersheds studied by Cook et al. (2015, 2020), respectively, were both characterized by steeper average slopes and fewer upstream water bodies likely to trap fine sediment relative to the Ossipee watershed. Despite these factors, Euro-American settlers were undoubtedly modifying the regional landscape over the past 250+ yr, and at least some of the sediment liberated by land-use changes has likely contributed to elevated $MAR_{clastic}$ since at least 1890 CE. The increasing content of clastic material in the centuries preceding the uppermost event deposit, evident from decreasing LOI and increasing ρ_{db}, magnetic susceptibility, and potassium (Fig. 6), may record the subtle, early impacts of Euro-American land-use changes. Collectively, these results suggest that while both hydrologic and human disturbances to the landscape may increase sediment availability and mobilize sediment in portions of a watershed, the export of fine-grained sediment from the largest watersheds in the region likely displays a muted response to landscape disturbances. This finding has important implications regarding the potential magnitude of the impacts from Euro-American land-use changes on the redistribution of sediment across the northeastern United States over the past few centuries.

CONCLUSIONS

Ossipee Lake preserves a continuous record of watershed erosion spanning the late glacial and the entirety of the Holocene through the period of regional Euro-American settlement. Variability in sedimentation throughout the record reflects ongoing paraglacial landscape adjustment. The period of most active landscape adjustment persisted until ~12,000 cal yr BP. Decreasing mass accumulation of clastic sediment from 12,000 to ~9000 cal yr BP reflects the gradual stabilization of the landscape as river channels approached equilibrium profiles, extensive forests were established, and the most readily available sediment supplies were exhausted or isolated. An apparent trend of increasing sediment yield from 9000 cal yr BP through 1850 CE is consistent with increasing effective precipitation over this period and suggests a dominant hydroclimatic control of erosion on long timescales. However, the overall sediment yield and magnitude of changes in sediment yield from the Ossipee watershed remain low throughout the Holocene, suggesting a relatively low sensitivity to change and minimal impact from millennial-scale changes in vegetation or regional fire frequency. A muted response to Euro-American land-use changes and lack of distinct depositional signatures related to known extreme floods or historical land-use activity further reflect the lake and watershed system's limited sensitivity to disturbances. Downstream export of fine-grained sediment is limited by trapping and storage among hillslope, floodplain, lake, and wetland depocenters that become increasingly abundant as watershed size increases. This result suggests that the export of fine-grained sediment from the largest watersheds in the region likely experienced a modest response to Holocene landscape changes.

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Data Availability Statement. Data related to this study are available at https://doi.org/10.7910/DVN/6BAMHR (N.P. Snyder, T.L. Cook, J. LeNoir, 2022, "Data from Sediment Cores and Surveys of Ossipee Lake, New Hampshire, USA.")

Supplementary Material. The supplementary material for this article can be found at https://doi.org/10.1017/qua.2022.54.

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