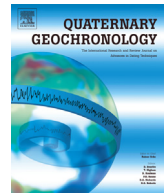




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Research paper

Construction ages of the Upton Stone Chamber: Preliminary findings and suggestions for future luminescence research

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ABSTRACT

The Upton Chamber in Massachusetts, an earth-covered stone structure 3.4 meters (m) in diameter, with a corbelled stone dome, and a 4.3 m long entrance passageway, is studied with the aim of determining whether optically stimulated luminescence (OSL) dating methods can be used to establish the approximate construction date of the entranceway. Three samples, taken from soil behind the lowest stones in the wall of the entrance passageway, returned OSL ages between 385 and 660 years ago (or from 1625 A.D. to 1350 A.D.; using the year 2011 as the 0 year). One sample, taken below the bottom of the artifact layers in an archeological test pit in front of the chamber entrance, returned OSL ages between 650 and 880 years ago. A modern sample collected from a nearby fluvial channel returned an age between 55 and 175 years. The Upton Chamber OSL sampling results are challenging to interpret because there are mixtures in the samples of both younger and older grains that likely result from human modification, root or soil processes, animal bioturbation (i.e. ants and worms), and/or partial bleaching. The ages were determined using the lowest component of the finite mixture model as applied to a distribution of quartz grains. Further research may enable us to determine whether older components are of anthropomorphic or geological origin.

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1. Introduction, previous studies, and research questions

Although optically stimulated luminescence (OSL) has commonly been used at other pre-European contact archeological sites throughout the United States (e.g. Topper (Waters et al., 2009), Buttermilk Creek (Waters et al., 2011), Cactus Hill (Feathers et al., 2006), etc.), within the Northeastern area of the United States (i.e. the New England area) it has not been routinely applied. More than 300 stone chambers of unknown origin, construction periods, and functions have been cataloged in New England (Whittall, 1981, 1982; and 1984). A chamber located in Upton, Massachusetts (Fig. 1) with an interior domed chamber 3.4 m in diameter and an entrance passageway that is 1 m (width) x 4.3 m (height), is among the largest of these structures (Fig. 2A).

The land on which the chamber is located was inhabited solely by the Nipmuc Indians until 1704 A.D. (Supplemental Fig. S8). The

chamber is on the route of an important Native American trail referred to today as the Old Connecticut Path, which connected Boston with the Connecticut River near Hartford. To the west was the 'Praying Indian Village' of Hassanamisco, a four square mile area designated by John Eliot in 1654 as a place for 'Christian Indians.' According to Eliot, the Indians selected Hassanamisco because it was 'the place of their desires' (Eliot, 1670). "Upton was established as a town in 1735 from parts of Hopkinton, Mendon, Sutton and Uxbridge. During the Plantation Period (1620–1675), the southern portion of Upton was included in the 1667 Mendon Grant, while the northern section was unincorporated. No notable colonial settlement took place during this period" (Dudek, 2012).

In 2011, the Federal Communications Commission (FCC) in Washington, D.C. made a determination that the cultural landscape known as the Pratt Hill–Upton Chamber Historic District is a discontinuous historic district that is eligible for listing on the National Register of Historic Places (under Criterion A for its role in the religious and cultural traditions of three tribes—the Narragansett Tribe, the Wampanoag Tribe of Gay Head (Aquinnah), and the Mashpee Wampanoag Tribe). Based upon the limited excavation

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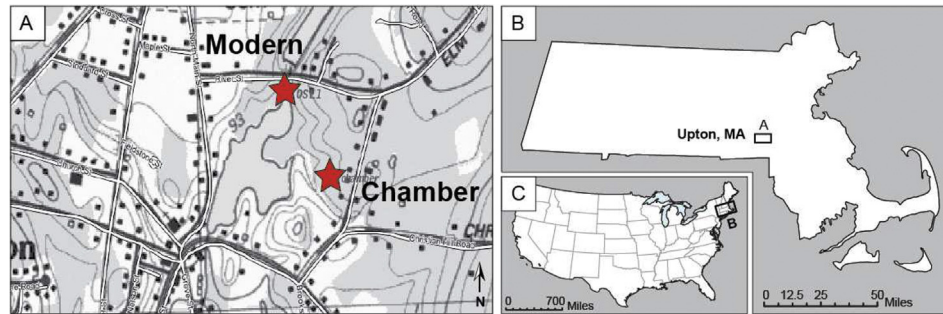


Fig. 1. A. The placement and elevation of the Upton Chamber in Upton as well as the site of the modern creek sample. The Upton Chamber is located within the USGS Milford Massachusetts 7½-minute quadrangle map and can be found at N 42° 10' 32.8" and W 71° 35' 54.4", NAD27 CONUS. B. Location of Upton within the state of Massachusetts (labeled A). C. Location of the Upton, Massachusetts area within the eastern United States (labeled B).

from the site examination, the Upton Chamber is also recommended as eligible under Criterion D: Information Potential ("has yielded, or may be likely to yield, information important in pre-history or history"), at the local level (Dudek, 2012).

The New England Antiquities Research Association (NEARA) and the Upton Historical Commission (UHC), with additional private donors, have accordingly initiated new research (Martin, 2011a) with OSL techniques using single grain and single aliquot dating for the sediment at the entranceway to Upton Stone Chamber. In particular, the question OSL would answer is: what are the ages of construction?

The geology of the region is well documented in surficial geologic maps (Stone and Stone, 2006) and most landforms in the area are a direct result of the glacial retreat of continental glaciers some 14–16 ka after a terminal position established about 21 ka ago (Hildreth and Stone, 2004). The area of the Upton Chamber contains a fine sandy loam derived from glacial stratified deposits. The soil type is "Canton soil"; it varies in depth from 46 cm to 91.5 cm and is formed directly atop the glacial till (Al Averill, U.S. Dept. of Agriculture, written communication, 2014; Figure S9). Upton Chamber is at the junction of two streams, which may explain the abundance of glacial outwash sand in the area of the chamber.

The aim of this study is to document the sampling, present and discuss OSL measurements, and determine ages of sediment taken from behind the lowest stones in a wall during the masonry reconstruction of the Upton Chamber. Questions that will be considered are:

- i) Does OSL dating provide definitive dates for the time of construction for the entranceway to Upton Chamber?
- ii) When multiple OSL equivalent dose (D_E) populations are evident in samples, which age model is the best to use and why? and
- iii) Do the OSL D_E populations provide any information about the methods of construction?

2. Methods

2.1. Sampling

On the 25th and 26th of October, 2011 samples were taken under the supervision of the archaeological firm James Milner Associates, Inc., during the masonry rehabilitation of the destabilized and slumping capstone of the entrance passageway (Dudek, 2012). Ten samples for OSL dating were obtained, with the result that three from within the chamber wall and one from an excavation pit in front of the chamber were analyzed for OSL during 2012 and 2013. At the chamber entranceway, samples of gravelly sediment

were collected from behind the lower half of the southerly wall at locations shown in Fig. 2B and Table S7, and in front of the entrance as shown in Fig. 3C. A modern stream sample was also collected in 2014, as shown in Figs. S6 and S7. Photographs similar to Fig. 3A–C (listed in Table S6) were made of each sampling step as a 10-cm long steel tube of 4 cm diameter was driven into undisturbed soil to obtain an unexposed sample, and the tube was quickly stored in a black, light-tight bag. Then approximately a liter of sediment was dug out around the sample hole and stored in a plastic bag. A detailed report is archived (Martin, 2011b; Tables S6 and S7; Supplemental Notes #1, Figs. S10–S30).

2.2. Luminescence lab protocol

2.2.1. D_E calculations

The OSL technique relies upon the fundamental principles of radiation dosimetry, whereby a grain of sediment will be exposed to sunlight on its journey, lose its prior luminescence signal, and then be deposited in a final resting place at a "zero" or bleached level. Natural processes of low-level sediment radiation then act to fill the sediment grain again with luminescence, such that the time of deposition (or age) can be determined if two things are accurately measured: (i) the level of incoming radiation that stimulates luminescence growth (the dose rate or D_R) and (ii) the level of luminescence currently held in the grain of interest (the D_E).

The steel tubes were only opened under "safe light" (sodium vapor lighting) conditions in the luminescence laboratory once they were received. After discarding about 3 cm from both opened ends, the entire volume of the middle of the tube was treated in 10% hydrochloric acid (HCl) for 24 h (to dissolve any post-depositional carbonate coatings), 35% H_2O_2 for 24 h (to dissolve the organic and soil carbonates), sieved to collect coarse-grained fractions (with grains ~ 250- and 180 μ m in diameter) and 50% hydrofluoric acid (HF) for 50 min (to dissolve surface impurities such as iron oxides from the quartz grains). Before the HF, the coarser grained size (250–180 μ m) quartz fractions were separated from the feldspars and any heavy minerals using a Frantz magnetic separator and heavy liquids (lithium sodium polytungstate or LST) ($\rho = 2.58 \text{ g cm}^{-3}$ and $\rho = 2.67 \text{ g cm}^{-3}$). After pouring off the HF solution, we put the sample in 25% HCl for 5 min (while in the ultrasonic bath) and finally re-sieved to winnow broken feldspar grains.

All samples were measured for single aliquot and then separately as single grain D_E by loading 100 grains onto a special aluminum disc. We analyzed 2400 grains for each sample except the modern which was only analyzed for 1200 grains because grains of the desired size were in short supply (the modern stream has much coarser grains in the bed load). Irradiation and heating are performed on these discs as a whole, but each grain position is

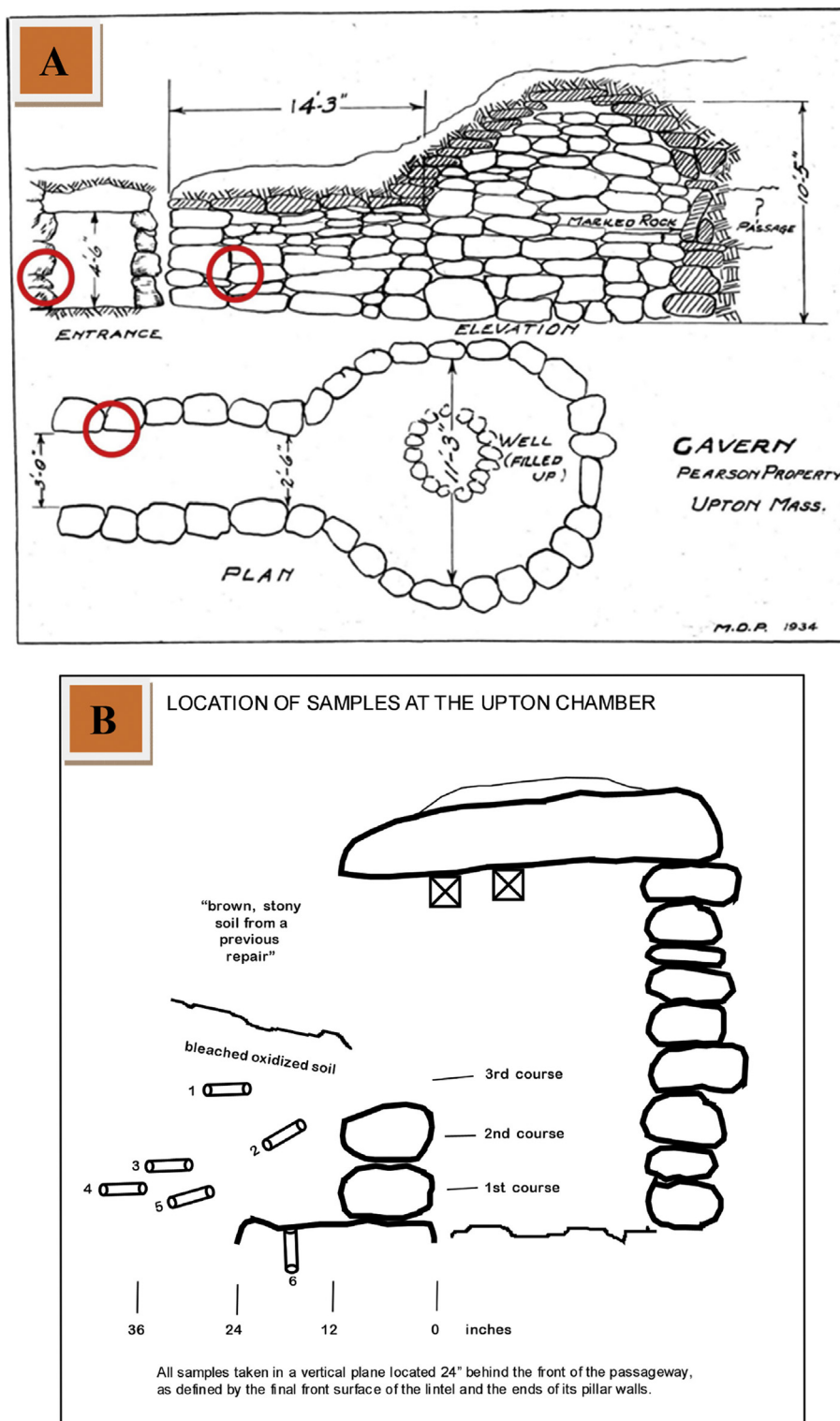


Fig. 2. A. Red circles mark the sampled area in the entrance passageway (adapted from a drawing of Malcom D. Pearson; published in Goodwin, 1946). B. Section through entrance passageway and backfill area during repair work, showing locations at which OSL samples were taken (Reprinted from Martin 2011b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measured for emission by a focused laser using green wavelength (focused to 20 μm in diameter; Bøtter-Jensen et al., 2010). Stimulation optics used were a 10 mW Nd:YVO4 solid state diode-pumped laser emitting at 532 nm attached to a Riso TL-DA-15 reader. The “raw data values” accepted from each population in D_E values are included in Table S3.

Following the standard SAR procedure (Murray and Wintle, 2003; Wintle and Murray, 2006), the grains were irradiated with a beta source of calibrated intensity. Beta radiation was applied using a 25 mCi $^{90}\text{Sr}/^{90}\text{Y}$ in-built source (see Table S1 for details). Detection optics were comprised of two Hoya 2-U340 filters coupled to an EMI 9635 QA Photomultiplier tube.



Fig. 3. A. David Stewart-Smith hammers the steel pipe into which sediment for OSL dating will be collected behind stone “d” of the first course in the entranceway to the chamber. B. Peter Wiggin shores up the entranceway to Upton Chamber during repairs. C. Upton #9 and #10 were taken in front of the entranceway with archeologist Marty Dudek (arrow points to OSL collection pipe). All photos provided by Fredrick Martin from [Martin \(2011b\)](#).

All sample aliquots were run at 200 °C for 10 s, after testing for preheat at three temperatures, 200 °C, 240 °C, and 280 °C. Several quality-control criteria were employed to reject OSL signals and resultant SAR D_E values. Data rejection criteria were similar to those in common practice ([Wintle and Murray, 2006](#); [Table S2](#); [Fig. 4A–C](#)) with the added caveat that grains with D_E values <0.2 Gray (Gy) were discarded because three sources of error were >20%; signal to noise ratio on instrumental background levels, relative uncertainty on natural test-dose response, and recycling values ([Medialdea et al., 2014](#)).

The growth of the luminescence with increasing dose was well represented by a simple linear function and illustrates the generally reliable behavior of the quartz samples for the SAR protocol ([Fig. 4C](#)). We accepted data having recycle ratios within 10% of 1 and recuperation ratios ([Aitken, 1998](#)) within 2% of 0 when recuperation was >20% of the normalized natural signal (L_x/T_x ratio) and test-dose-signal errors were <10%. We forced dose–response curves through a zero origin. Dose recovery tests were also performed to ensure that the sediments were responsive to optical techniques and recording reproducible D_E values. Samples that failed any of these tests, exhibited unstable OSL signals, or that did not yield reliable SAR D_E values were excluded from further analysis ([Wintle and Murray, 2006](#); [Rhodes, 2011](#)).

We then calculated the statistical indices of mean, median, standard deviation, standard error, scatter (overdispersion) in the D_E measurements, and applied the finite mixture model (FMM) ([Galbraith, 2005](#); [Galbraith and Roberts, 2012](#)) to calculate the D_E population that was most likely (see Supplemental notes on FMM for details). The experimental results showed varying evidence of partial bleaching and/or multiple age components with overdispersions at 82%–172% (the modern sample showed 98% overdispersion; [Fig. 5A–E](#)).

2.2.2. Dose rate (D_R) calculations

Most ionizing radiation in the sediment that gives rise to the luminescence phenomenon is from the decay of isotopes in the uranium (U) and thorium (Th) decay chains and the radioactive potassium (^{40}K) element, cosmic dose contributions, with minor contributions in the beta chain from rubidium (^{87}Rb). The high-resolution gamma spectrometer provides isotopic discrimination of gamma rays; correspondingly, beta and alpha D_R s may then be estimated. D_R was obtained using elemental concentrations (K, U, Th, and Rb) following the procedures described on the U.S. Geological Survey (USGS) web site <http://minerals.cr.usgs.gov/icpms/intro.html> and by [Snyder and Duvall \(2003\)](#).

Measurement of the D_R was severely limited for two reasons; a

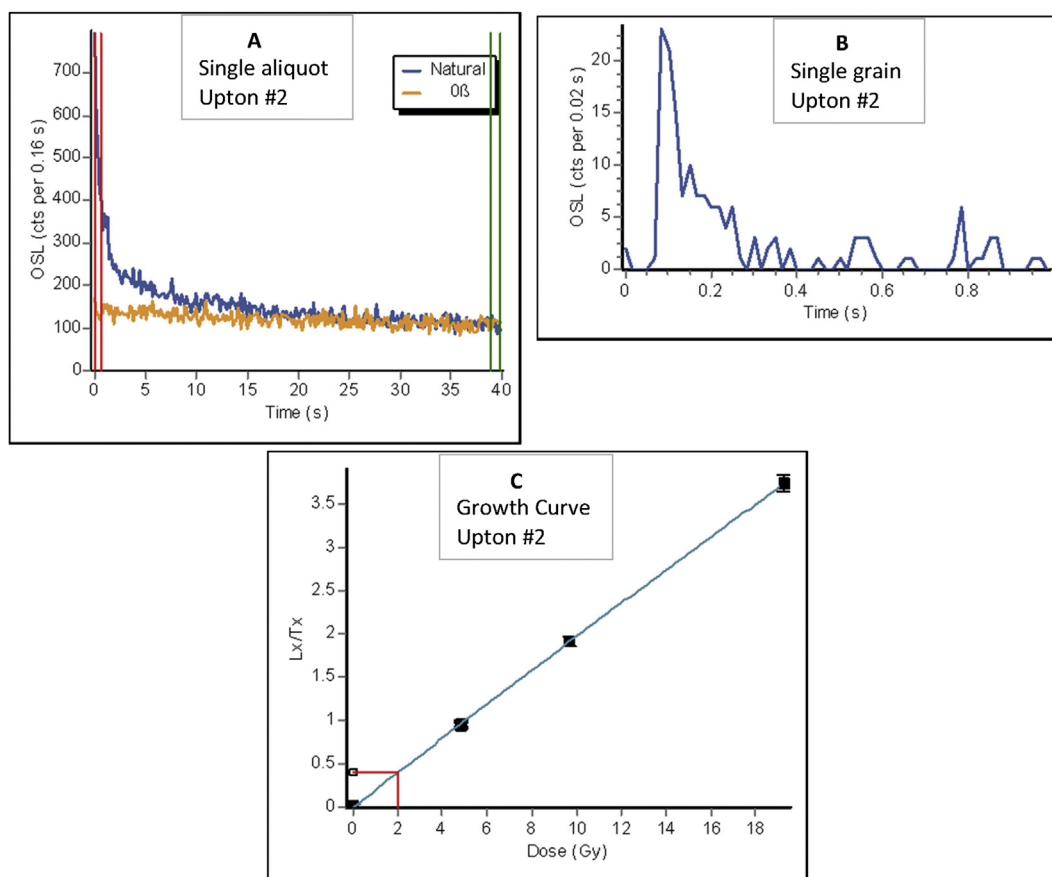


Fig. 4. A. An OSL decay curve for Upton #2 sample showing the quartz signal as measured with blue-light wavelength emitting diodes on single aliquots. The second curve shows the residual level of the aliquot without exposure to the beta source. B. For comparative purposes, a growth curve for single grain data from Upton #2 is shown after 1 s of stimulation from a green light laser. C. Single aliquot growth curve for Upton #2 sample, with the natural (red lines) near 0.5 on the x-axis. The x-axis is the equivalent dose measured in Gy (shown circles are obtained by varying Gy). The y-axis shows the luminescence response over the test dose response (L_x/T_x or unitless normalized OSL sensitivity measurements). All Upton samples were calculated with a linear fit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

portable gamma spectrometer was not available for in-situ counting and $\text{CaSO}_4:\text{Dy}$ dosimeters could not be inserted and left to be recovered as the sediment behind the walls would not be accessible after repair work. Nevertheless, using best practices from current literature (e.g., Aitken, 1985; Duller, 2008; Feathers et al., 2008), samples for the D_R were collected in bulk sediment (in a circular fashion around the sampling hole) and data was combined with elemental concentrations taken from USGS rock calibration standards (G-2; Rhode Island SDC-1; Washington DC) (Supplemental Notes on gamma attenuation calculations; values were averaged for use in Table 1). This collection of elemental concentrations produced D_R s which produced values in the range of 1.8–3.4 Gy/ka (Table 1). Cosmic-ray D_R data were estimated for each sample as a function of depth, elevation above sea level, and geomagnetic latitude (Prescott and Hutton, 1994).

At Upton Chamber, the stones are of granite (Johnson, 1984) and are placed as walls to the entranceway and chamber (Fig. 3A and B). We sampled sediment behind these walls but the boulders were not directly sampled for chemical analyses and their D_R s are likely to be much higher than the enveloping sediment (Baran et al., 2003). Their presence within 30 cm of an OSL sample would result in D_R s which are higher than those calculated from only sediment, therefore the bulk samples were treated as follows: we assume that samples Upton #4 and #5 (Fig. 2B, distance from rock wall >50 cm) had dose rates only from the sediment and Upton #2

(Fig. 2B; distance from rock wall 20–35 cm) had alpha and beta from the sediment and gamma dose rates increased 7% because of the proximity of the rock, as explained below. The modern sample and Upton #10 were not taken near the rock walls.

The effect of a rock wall which intersects the edge of the collection sphere around a sample differs from models in which rock is dispersed throughout the volume of the sphere (Baran et al., 2003). The collection sphere is approximated as being 30 cm in radius (Aitken, 1985) since this is the area of maximum penetration by gamma rays. Upton #2 is listed as being 45 cm from the front of the rock wall, with the rock wall varying in thickness from 20 to 30 cm. Thus the rear surface of the wall was estimated to be 15–25 cm from the center of the sphere. Calculation for a wall 15 cm from the center of a 30 cm sphere shows that it fills only 15% of the active volume of the sphere. Further, only about 22% of the emission from this volume reaches the center because the gamma rays are scattered by the 15 cm of intervening sand.

The net result of the wall is about a 7% decrease in dose rate because some sand has been removed, and a 14% increase because the more radioactive rock (Table 1) has been substituted for the sand, resulting in a 7% increase in the actual dose rate above the experimentally measured dose rate of the sand alone. The corrected age of 535 years (for an average wall thickness of 20 cm) and the uncorrected age of 575 years are listed in Table 2, with the remark that systematic error is not likely to put the age in excess of 500

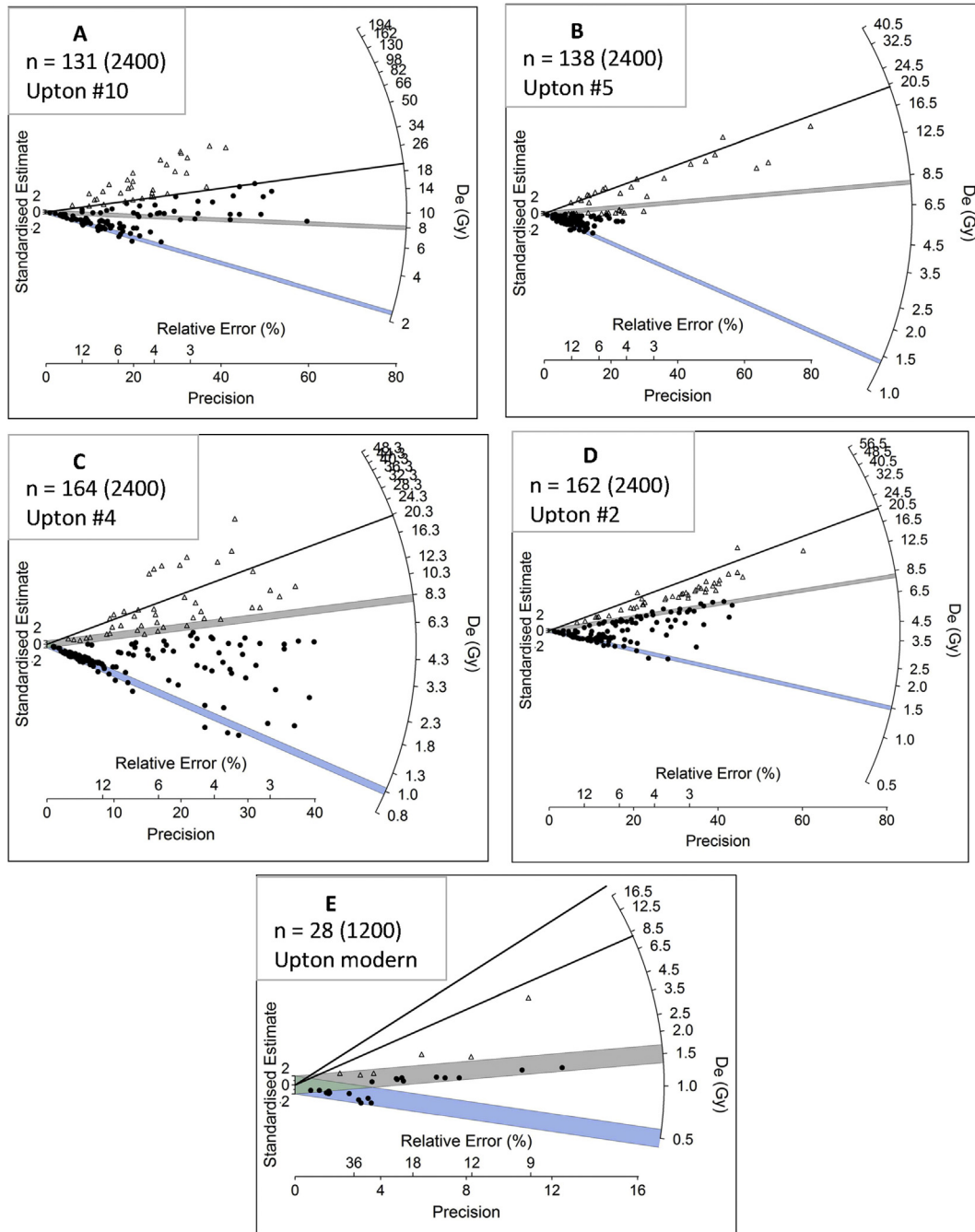


Fig. 5. A–E. Radial plot graphical analyses for all samples. The blue bar shows results of populations that are the lowest dominant D_E values. Consistently higher D_E populations were highlighted with a grey colored bar at 8 Gy, while the partial bleach trend at 20 Gy was also fitted with a single trend line. Outliers, shown as open triangles, suggest a 60 Gy component, which is absent in samples closer to the wall. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

years. Details of the complete calculations can be found in the supplemental material notes on gamma attenuation calculations in sediment and rock.

The amount of water within the pore spaces of sediment will greatly decrease the amount of incoming radiation to the sample grains. An increase of 1% in moisture content increases the age by roughly 1% (Aitken, 1985; Jacobs et al., 2008). For this reason, it is very important to have as accurate an estimate as possible of probable year-round water content of the soil. Water content of the sediment samples was measured between 23% and 6% of saturation while in the field. Complete saturation was determined to be at

most 33–23% of the dry sample weight by lab measurements. In other words, the maximum amount of water saturation is 33–23% of the dry sample weight. It is prudent to suppose that 50–75% of maximum moisture is a reasonable long-term average.

For purposes of estimating field moisture, we note the present floor level of the chamber is usually quite wet, with water in it much of the year; the water table presently sits very close to the surface of the chamber floor. It is likely that this problem occurred when the area in front of the chamber was filled in with earth fill around 1950. Formerly the chamber was dry most of the year, with water mainly present in the spring. The filling of the adjacent

Table 1

Dosimetry and elemental concentrations of samples from Upton Chamber and area.

Sample	% H ₂ O content ^a	^b K%	^b U (ppm)	^b Th (ppm)	D _{cos} (Gy/ka) ^c	D _β (Gy/ka) ^c	D _γ (Gy/ka) ^c	Dose rate Gy/ka ^d
Upton #2 (sediment)	9 (32)	1.86 ± 0.04	1.88 ± 0.23	9.25 ± 0.46	0.202	1.474	0.888	2.57 ± 0.18
Upton #2 (stone)	—	3.88 ± 0.12	3.10 ± 0.20	18.5 ± 1.45	0.202	3.439	1.997	5.64 ± 0.29
Upton #2 (sediment + stone)	—	2.37 ± 0.06	2.19 ± 0.22	11.6 ± 0.71	0.202	1.596	0.958	2.76 ± 0.19
Upton #4	6 (25)	1.05 ± 0.03	1.87 ± 0.25	5.85 ± 0.42	0.191	0.962	0.616	1.77 ± 0.17
Upton #5	17 (23)	2.40 ± 0.04	2.34 ± 0.14	11.2 ± 0.40	0.190	2.044	1.201	3.43 ± 0.16
Upton #10	23 (33)	2.36 ± 0.04	2.09 ± 0.25	9.65 ± 0.53	0.192	1.782	1.008	2.98 ± 0.20
Modern	22 (24)	2.38 ± 0.06	1.81 ± 0.23	6.44 ± 0.25	0.289	1.751	0.883	2.92 ± 0.16

^a Field moisture, with figures in parentheses indicating the complete sample saturation %. Dose rates calculated using approximately 50–75% of saturation values.^b Analyses for the sediment were obtained using laboratory Gamma Spectrometry (high resolution Ge detector).^c Relative contributions from beta, gamma, and cosmic doses to the overall dose rate.^d Dose rate for 250–180 microns quartz sand. Errors at two sigma. Cosmic doses added using Prescott and Hutton, 1994.

lowlands has raised the water table and even flooded the Upton Chamber within living memory (Dudek, 2012).

Samples (Upton #2, #4, and #5) from the chamber wall should be above the modern historic water table and a 50% of saturated water content for age calculation is reasonable. For sample Upton #10, from a pit section below the entranceway floor, 50% (in-situ) plus 25% saturated water content for long-term average is more reasonable than 50% saturated content. To more readily illustrate the difference in ages for water content, consider that Upton #4 at 10% water content would be approximately 495 years, the age at 25% water content would be 510 years, while the age at 50% water content is 580 years.

Specification of the appropriate gamma dose contributions, water content, and the effect on D_R calculations were determined using methods described above. Ages are presented in calendar years (0 yr = 2011 A.D.) and uncertainties are given at the 95% (2σ) confidence level in contrast to traditional reported values in the luminescence literature (which are usually given at the 68% (1σ) level) because the samples are young (<1000 years old) and to facilitate comparison with future isotopic geochronology methods (Table 1 and Table 2).

3. Results and discussion

3.1. Does OSL dating provide definitive dates for the time of construction for the entranceway to Upton Chamber?

Table 2 lists the ages for the five samples, as measured and modeled from the most recent component determined by the FMM as discussed below. The results for these three samples (Upton #2, #4, and #5) taken behind the wall agree with each other (within error) and indicate the sediment was exposed to light sometime between 1350 and 1625 A.D. (rounded slightly), from ages of 535 ± 80, 580 ± 80, and 455 ± 70 years (with an average age of 523

years). Thus, the earliest construction intervals on the entranceway to Upton Chamber put establishment as early as 1350 A.D. (Upton #4), while Upton #2 and Upton #5 place the latest limit (at the 95% confidence level) of construction from 1555 to 1625 A.D.

Upton #10, the age of the sediment on which the chamber was built, was worked or exposed between 1130 and 1360 A.D. This sample does not show any traces of the younger component seen in all the entranceway samples rather it shows a slightly older OSL age (Fig. 5A to E). Thus we speculate that the sediment in front of the chamber may be a ground level base on which the chamber walls were later built.

The data allow for the idea that the entrance to Upton Chamber could have been constructed over a long period of time. Grain populations from 4.5 to 7 Gy (ca. 530 BC) are in the modern, Upton #2, Upton #4, and Upton #5 but not Upton #10. Populations at 13–18 Gy (ca. 4200 BC) are in all the samples except the modern (Fig. 5A–E; supplemental FMM notes). The population at 13–18 Gy may be associated with either geological effects (Alexanderson et al., 2008; Mahan et al., 2015) or anthropological activities (Baran et al., 2003). These ages are too young to be associated with glacial outwash, but may reflect other geomorphic transformations since that time (e.g. soil formation, fluvial reworking on an annual spring flood basis, or catastrophic events such as hurricane storms) although we also allow the possibility that the chamber could have experienced multiple stages of construction and repair. An examination and age of the local Canton Soil that developed atop the tills and outwash (Stone and Stone, 2006) is needed to see if it contains components that are seen in the D_E of the OSL measurements.

3.2. When multiple OSL D_E populations are evident in samples, which age model is the best to use and why?

Analytical models and elicitation of components were considered for four models;

Table 2

Data and OSL ages of samples from the Upton Chamber and area.

Sample	Dose rate Gy/ka	Equivalent dose (Gys) ^a	Equivalent dose (Gys) ^b	N ^c	% Scatter ^d	Age (years) ^e
Upton #2 (uncorrected)	2.57 ± 0.18	3.85 ± 0.28	1.48 ± 0.21	162 (2400)	82.3	575 ± 90
Upton #2 (corrected)	2.76 ± 0.19	3.85 ± 0.28	1.48 ± 0.21	162 (2400)	82.3	535 ± 80
Upton #4	1.77 ± 0.17	2.22 ± 0.23	1.02 ± 0.13	164 (2400)	172	580 ± 80
Upton #5	3.43 ± 0.16	2.57 ± 0.34	1.56 ± 0.23	138 (2400)	113	455 ± 70
Upton #10	2.98 ± 0.20	5.93 ± 0.44	2.28 ± 0.34	131 (2400)	142	765 ± 115
Modern	2.92 ± 0.16	1.28 ± 0.31	0.33 ± 0.17	28 (1200)	97.8	115 ± 60

^a The summation method uses the mean of the equivalent dose measurements.^b The summation method uses the finite mixture model for the equivalent dose measurements.^c Number of grains that yielded OSL measurements and were used to calculate the total D_E. Figures in parentheses indicate total number of grains that were loaded into the reader.^d Defined as "overdispersion" of the D_E values. Obtained by taking std deviation over the average. Values >50% reflect poorly bleached or bioturbated sediments.^e Age for 250–180 microns quartz sand. Linear fit used on equivalent dose, finite mixture model used to obtain summation, errors to two sigma.

- i) the Leading Edge where the average of the lowest 5% of the grains are considered (Lepper et al., 2000),
- ii) The Central Age Model (CAM; Arnold et al., 2007) which is usually favored when dispersion is low (<25%),
- iii) The Minimum Age Model (MAM; Galbraith and Roberts, 2012) which is favored when there is high dispersion, and
- iv) The FMM, which is considered to be the best model to use with single grains (Galbraith and Roberts, 2012).

Using Upton #5 as an example, the leading edge technique gave an age of 270 ± 80 years (for a starting construction age of 1740 A.D.), the CAM gave an age of 410 ± 60 years (although we eliminated the outliers over 6 Gy; for a starting construction age of 1600 A.D.), the MAM gave an age of 360 ± 45 years (for a starting construction age of 1650 A.D.), and the FMM gave an age of 455 ± 70 years (for a starting construction age of 1555 A.D.) (Table 2). The age estimates made using the FMM meant that the spectrum would be generated by a mixture of a finite number of components computed and fitted to the actual data (Galbraith and Roberts, 2012; supplemental notes on the FMM) and observations at the time of sampling.

Although the D_E components suffered from overdispersion, the lowest component was used to determine the age. We are not able to assign a definite cause for the overdispersion in the components. A possible source of variation is non-uniform in-situ beta irradiation caused by varying coating thicknesses and mineralogy of the individual particles. The scatter could be traced to bioturbation but it is less likely, because although evidence for uniform mixing by bioturbation is provided by the similar components found in the chamber samples separated by tens of centimeters, there is little evidence for mixing from a younger source population (i.e. insect, earthworm, shrubs and grasses when the site was neglected; Duller, 2008; Rink et al., 2013, Fig. 3A–C; Figs. S10–15).

Because of the ubiquity of the overdispersion and the possible sourcing of it through bioturbation, the MAM and leading edge models are not appropriate. The CAM was also not appropriate due to the high overdispersion, although the ages from this model were generally in closest agreement with the FMM.

3.3. Does the nature of the OSL D_E populations provide any additional data about the methods of construction?

The FMM discriminates between specified D_E components in the data. These components can be visually highlighted within radial plots (blue and gray bars in Fig. 5A–E). The distribution of D_E s show an overall pattern of very high scatter or overdispersion. The lowest dose population in each radial plot is likely to be the most correct one for determining the age of the last entranceway construction or repair (Porat et al., 2012; Mahan et al., 2015). Upton #5 (Fig. 5B) has a tighter scatter than the other samples, but in all cases except Upton #10 (Fig. 5B–E) it is clear that there is a persistent population of low D_E values between 1.0 and 1.5 Gy. There are several other easily distinguished component levels at 4.5–7 Gy (except for Upton #10), 13–18 Gy (except the modern), and 60 Gy for only for Upton #4 (weakly) and Upton #10 (see also Table S3 and notes of the FMM analyses).

Original sediment source material would not have been well bleached during glacial outwash events and subsequent fluvial reworking largely creating the overdispersion seen in the D_E . We postulate that the components at 4.5–7 Gy may be geological in nature while the 13–18 Gy components are more likely to be geological in nature. Geological origin of the 13–18 Gy component is favored by the appearance of these in sample Upton #10. A possible scenario emerges. The 60 Gy component is likely to be related to glacial processes (i.e. outwash), the 13–18 Gy component

could be bleached from outwash by some unknown geological event, the 4.5–7 Gy component bleached from both sources by a second geological or partial bleaching anthropological event (i.e. backfill not completely zeroed during excavation), and the 1.0–1.5 Gy component bleached from the others by a recent flooding event or actual entranceway or chamber construction.

Alternatively, the cause of the overdispersion in the Upton Chamber samples may be viewed as the result of anthropogenic manipulation during construction. As the passageway was built or repaired, it may have been backfilled with fully bleached grains forming the 1.5 Gy components, which were then mixed with nearby non-bleached glacially derived sediment of 4.5–7 Gy and 13–18 Gy by bioturbation. A similar possibility, which we cannot rule out, is that all three components at 1.0–1.5 Gy, 4.5–7 Gy, and 13–18 Gy result from two repairs and an initial construction, with grains mixed together by bioturbation. This model would explain why Upton #4, taken 0.7 m behind the chamber wall, has a weak 60 Gy component, resulting from mixture with the Canton soil at the back side of the builder's trench, while Upton #2 and Upton #5 lack the 60 Gy glacial outwash component, because they result from successive human activities in sunlight inside the builder's trench. A bimodal or strongly skewed distribution interpreted as anthropogenic is indeed the finding of similar investigations where glacial outwash was not involved (Baran et al., 2003; Huckleberry and Rittenour, 2014).

The modern sample (Fig. 5E) was taken from a fluvial channel between Mill Pond and Pratt Pond and has an age range of 175 to 55 years, as is expected for a modern fluvial sand, but it also has the persistent 1.0–1.5 Gy component as seen in the three wall samples. This leads us to speculate that a flood may have occurred (above the level of Upton #10) which damaged the entrance passageway and required a repair to the chamber.

We acknowledge that a great variety of assumptions can undermine even the most careful study. As alluded to earlier, these include: an inaccurate calculation of the water content of the sediment, surrounding boulders and sediment resulting in D_R s that are underestimated, high values of overdispersion as can be seen in our D_E , (e.g. caused by either heterogeneous bleaching of grains at deposition/construction, weathering effects, or variations in dosimetry for individual grains; Jeong et al., 2007), application of an incorrect age model, or lack of another chronology for confirmation or evaluation.

It would be of great value for the history of the Upton Chamber to be able to date samples from its dome structure rather than the passageway, from samples placed to determine the extent of the builder's trench, if any, and samples of the nearby glacial outwash and Canton Soil. These samples would provide a better basis for a “meta-data” analysis at the site and also provide an increased understanding of whether there were multiple periods of repair, the variation of the dosimetry, and whether mixed sediment is pervasive at the site. Further evidence may show that the Upton Chamber is of greater antiquity than work on the entranceway can currently provide.

4. Conclusions

The three samples that were collected behind the wall of the entranceway to Upton Chamber (Upton #2, Upton #4 and Upton #5) returned ages of 535, 580, and 455 years with an average age of 523 years. When the errors are attached to the sample ages from the chamber entranceway, the returned ages are between 385 and 660 years ago (or 1350 A.D. to 1625 A.D.; using the year 2011 as the end year). Upton #10, taken below the bottom of the artifact layers in the archeological test pit located in the front of the entrance to the chamber, did not return the same ages as those in the chamber.

The age of this unit is between 650 and 880 years ago and most probably dates the surface the chamber was built on. These results put the origin of the entranceway to Upton Chamber before documented English settlement of the area. Although there was a European presence on the coastline in Plymouth in 1620 and in Boston in 1630, settlement close by in Mendon did not occur until 1660.

Sediment within Upton Chamber has either been disturbed through plant, water, and soil formation processes, or through animal biological processes, which may include human modification. The sediment also has partial bleaching components. These processes produce a widely dispersed OSL spectrum. When multiple components were evident in samples, the best age model to use was the FMM as it splits out components without bias. These components provide additional information about possible dates of construction. The youngest component was used to determine the entranceway age. Much older components of three different ages are inferred, which may be of geological or anthropogenic nature. OSL dating was successful in determining the last possible date for construction of the Upton Chamber entranceway.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quageo.2015.05.017>.

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