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Re: Dating Results for Voynich Manuscript Parchment Leaves 8, 26, 47 and 68, our reference AA84050, 49, 48, 47 respectively.

Dear Christine:

This letter details the sample treatment, measurement, and calibration of dates for four parchment samples obtained by me from the Voynich Manuscript at your facility on 15 January 2009. The list of samples, their masses and sampling locations are shown in Table 1.

Chemical Treatment

It was assumed that the parchment leaves had not been given conservation treatments in modern times, and therefore it was unlikely that synthetic coatings were on the parchment surfaces.

As suggested, one sample (from Leaf #68) was processed two times, with and without a solvent extraction procedure. The results indicated that the solvent extraction was necessary, so it was adopted for all subsequent samples.

The parchment samples were subject to sequential extraction by a solvent series comprised of hexane, ethanol, methanol, and water using a Soxhlet apparatus. The purpose of this treatment was to remove lipids and oils that might have accumulated in the parchment from handling. The samples were then given a standard chemical treatment (known as acid –base-acid or ABA) consisting of sequential extractions with mineral acids and bases. The objective of these is to remove acid and base soluble contaminants using carbon-free reagents.

After ABA treatment, the parchment samples were dried and combusted under vacuum in the presence of CuO to extract carbon as carbon dioxide. The carbon dioxide was cryogenically purified from the other products of combustion, and split into aliquots for carbon stable isotope measurement and 14C accelerator mass spectrometry.

Stable Isotope Measurement

The carbon stable isotope measurements (δ^{13}C values shown in Table 2), were obtained directly from aliquots of carbon dioxide gas. Aliquots were injected into a VG-Isotech Dual Inlet stable isotope mass spectrometer. The δ^{13}C values were measured with respect to PeeDee Belemnite, with a precision greater than $\pm$ 0.1‰. These measurements provide a preliminary assessment of sample identity and purity, and provide data necessary for the subsequent date calculations.

Accelerator Mass Spectrometry

Aliquots of CO_2 gas destined for the accelerator mass spectrometer were converted into graphite, a solid form of carbon, using the method of Slota *et al.* (1987). Radiocarbon measurements were made on a National Electrostatics 3.0 MeV Accelerator Mass Spectrometer. The samples were measured with respect to Oxalic Acid I (NIST SRM 4990), and the precision was $\pm$ 0.6 percent. [14]C ages were calculated using the equations in Donahue, Linick and Jull (1990).

Results shown in Table 2 are expressed first as "Fraction Modern", a ratio of the radiocarbon content of the sample over the radiocarbon content the reference "Modern" material (SRM4990). This value is used to calculate a Radiocarbon Age. Radiocarbon Age expresses the age of the sample in uncalibrated radiocarbon years before 1950 (years BP), using the ^{14}C half-life of 5568 years. The uncertainties are quoted as one standard deviation and reflect both statistical and experimental errors. The Radiocarbon Ages have been corrected for isotope fractionation.

The two measurements of Leaf #68 indicate a younger radiocarbon age for the sample that did not undergo solvent extraction. This pattern is consistent with the accumulation of more recent carbon, perhaps from handling. The measurements on the four leaves are tightly clustered, all falling within one standard deviation.

Calibration

Radiocarbon dating is underpinned by the assumption that in the past, ^{14}C levels in the atmosphere, and in living things, were essentially the same as they are today. In fact, atmospheric radiocarbon levels have undergone small but significant fluctuations. The conversion of a radiocarbon age to a calendar age requires that past atmospheric radiocarbon fluctuations are taken into account. This process is called calibration.

The calibration curve is the plot of atmospheric radiocarbon fluctuations versus time. It has been constructed from a very large series of ^{14}C measurements on tree rings. Tree rings were utilized because their age can be determined by independent means, the prosaic method of ring counting. Each ring defines a single year's growth. Because tree tissues are literally built out of atmospheric carbon, the ^{14}C content of a ring is determined by the ^{14}C level of the earth's atmosphere in that growth year. In essence, the rings of a single tree archive atmospheric ^{14}C levels over that tree's lifetime.

Moreover, the archives within individual trees can be combined by the science of Dendrochronology. Dendrochronology is the study of shared patterns in tree-ring widths within climatically related populations of trees. Using the shared pattern of ring widths in trees with overlapping life-spans, tree-ring sequences have been assembled using living trees and archaeological wood that continue back through the entire Holocene – a period of 12,500 years. High precision ^{14}C measurements down the ring sequence reveals peaks, valleys and plateaus in atmospheric radiocarbon levels. (They are due to complex changes in cosmic, atmospheric, and oceanic phenomena). This plot forms the basis of the Holocene Radiocarbon Calibration curve.

Operationally, calibration is essentially a comparison of the radiocarbon content of a measured sample to the radiocarbon content of tree rings in the dendrochronology sequence. When a cluster of rings is identified whose ^{14}C content matches that of the unknown, one deduces that all were alive at the same time. The age of the tree ring cluster (determined by ring counting) determines the age of the sample. Although it is a straightforward process, the peaks, valleys and plateaus in the calibration curve sometimes lead to complex results. Clusters of tree rings, sometimes living centuries apart, can contain identical levels of radiocarbon, making it impossible to assign a single age to the measured sample. Consequently, the precision of a calibrated date is highly variable. It all depends upon where the radiocarbon measurement falls on the calibration curve.

Calibration Plots

The calibration plots for the samples are shown in Figures 1 to 7. Calibrations were carried out using Atmospheric data from Intcal 04 (Reimer *et al.* 2004) and the software program OxCal v3.10 (Bronk-Ramsey 2002).

The Y-axis on the calibration plots is the Radiocarbon Determination, expressed as % modern. (Percent Modern is the percentage equivalent of the Fraction Modern value shown in Table 2.) The ^{14}C measurement is shown in red as the normal distribution projecting off the Y-axis. The width of the normal distribution reflects the measurement precision quoted in Table 2.

The calibration curve, from Reimer *et al.* 2004, is shown as the double blue line. The double lines bound the two sigma uncertainty of the known-age tree-ring ^{14}C measurements. The mean value of each measurement has been omitted for clarity.

The Black curve sitting along the X-axis is generated by the intersection of the red curve with the blue curve. This *is* the calibration. What results is a Calendar Date Probability Distribution. Its shape is determined by the intercepts of the radiocarbon measurement and its uncertainty, with the mean and uncertainties of the tree ring curve. Its complex shape results from the complex shape of the calibration curve.

The table in the upper right hand corner of each figure summarizes of the Calendar Date Probability Distribution. It is expressed as a series of calendar date ranges. Ranges created using 1 sigma uncertainty are listed under 68.2% probability, and ranges created using 2 sigma uncertainty are listed under 95.4% probability. A translation of the probability distribution into words is "There is a 95.4% probability that the true age of the sample falls within the range X AD to Y AD". If you want a narrower age range, then you become less certain the true age falls within the narrower range. Typically we quote the 2 sigma, or 95.4% range.

Averaging the Results to increase Precision

The precision of any measurement can be increased if measurements are repeated. Given the clustering of the dates for the four Soxhlet treated samples, and the nature of the object (a book), one can argue that in fact, a single object was measured 4 times. The mean and combined error of these four measurements was calculated using the formulae shown below. The results were 516 ± 18 radiocarbon years BP. Note that the measurement from solvent treated Leaf #68 was excluded from this average. The calibration plot of this date is presented in Figure 7. The advantage of combining dates is clear as the increased precision in the weighted mean value ends up simplifying the calibration plot to a single peak in the early 15th Century.

Formulae

Weighted Mean:

$$\mu = \Sigma(\ x_i/\sigma_i^2)/\ \Sigma(\ 1/\sigma_i^2)$$

Estimated Error of Mean:

$$\sigma_\mu^2 = 1/\ \Sigma(\ 1/\sigma_i^2)$$

Conclusion

It must be kept in mind that this exercise dated parchment, not when it was written on. That said, the clustering of the four measurements, and the calculated weighted mean gives strong evidence that the Voynich Manuscript was created in the first half of the 15th Century AD.

We hope this explanation is clear. Please don't hesitate to contact me with any further questions or comments.

Yours truly,

Greg Hodgins D. Phil.
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References

1. Bronk Ramsey, C. (1995) Radiocarbon Calibration and Analysis of Stratigraphy: The OxCal Program. *Radiocarbon* 37(2) 425-430.
2. Donahue, D. J., Linick, T. W., and Jull, A. J. T. (1990) Isotope-ratio and background corrections for accelerator mass spectrometry radiocarbon measurements *Radiocarbon* 32(2):135-142.
3. Slota, P.J., Jr., Jull, A. J. T., Linick, T. W., and Toolin, L. J. (1987) Preparation of small samples for ^{14}C accelerator targets by catalytic reduction of CO. *Radiocarbon* 29(2) 303-306.
4. Reimer P. J. *et al.* (2004) IntCal04 Terrestrial Radiocarbon Age Calibration, 0–26 cal kyr BP *Radiocarbon* 46(3): 1029-1058.
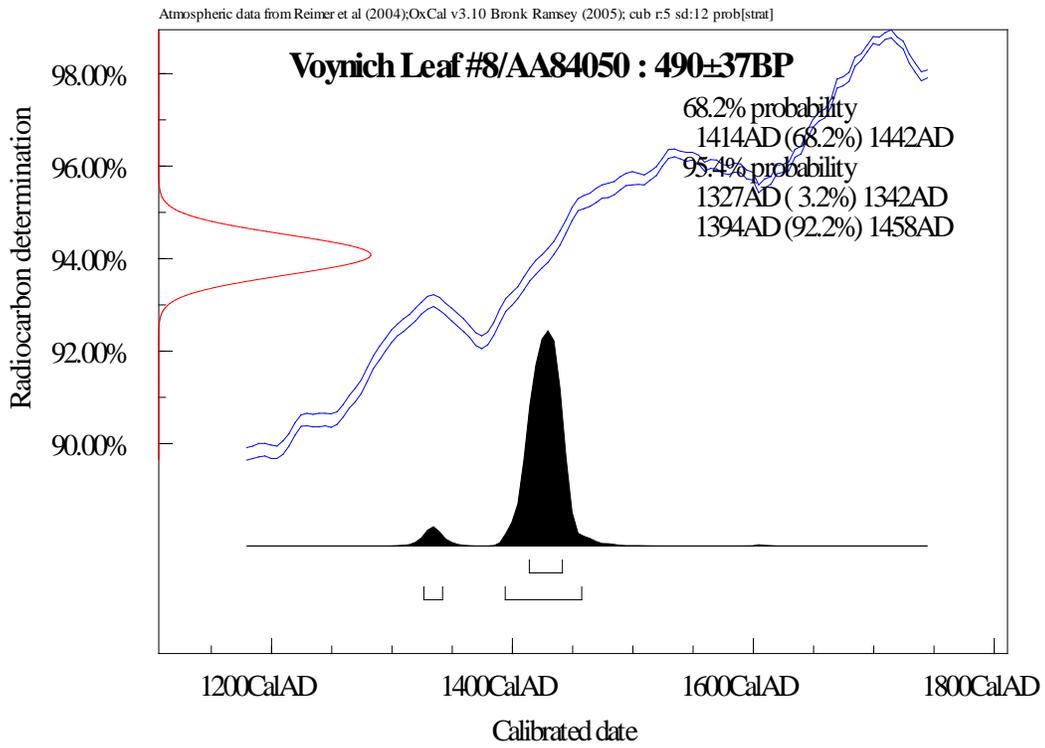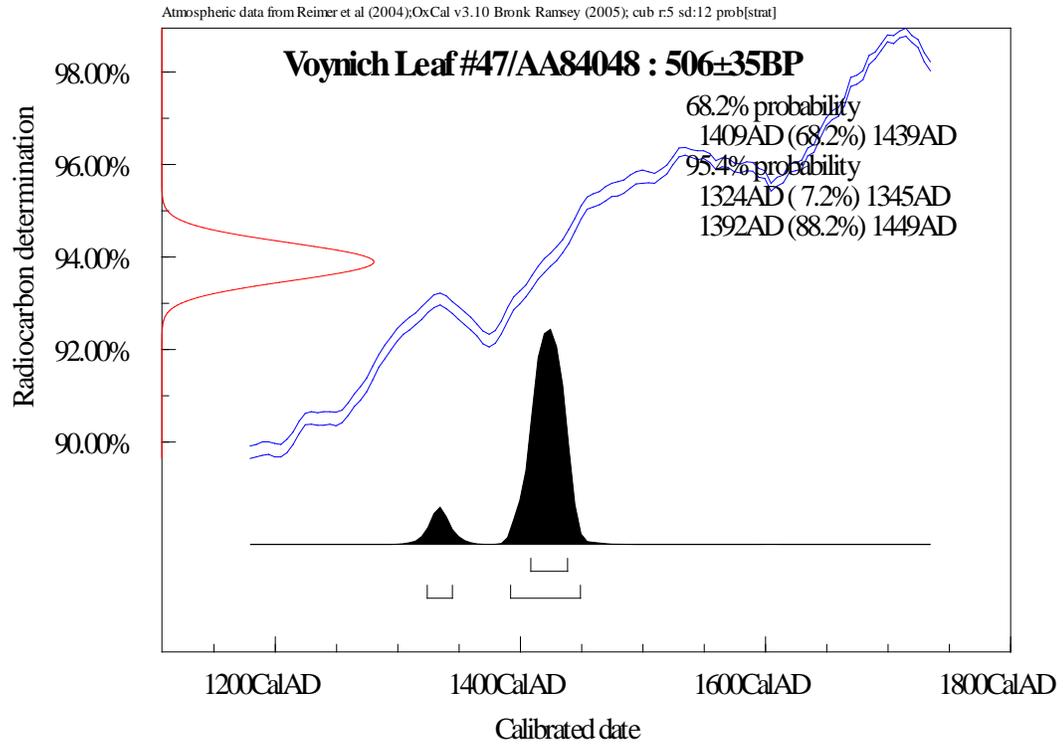
Figure 1: Leaf #8
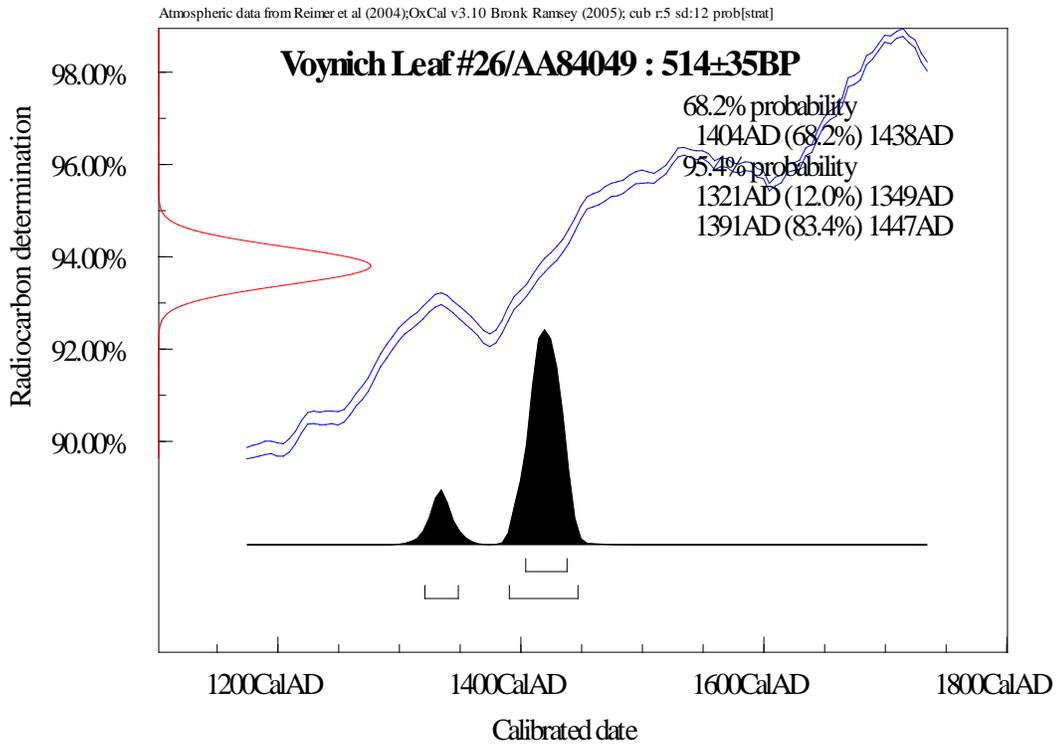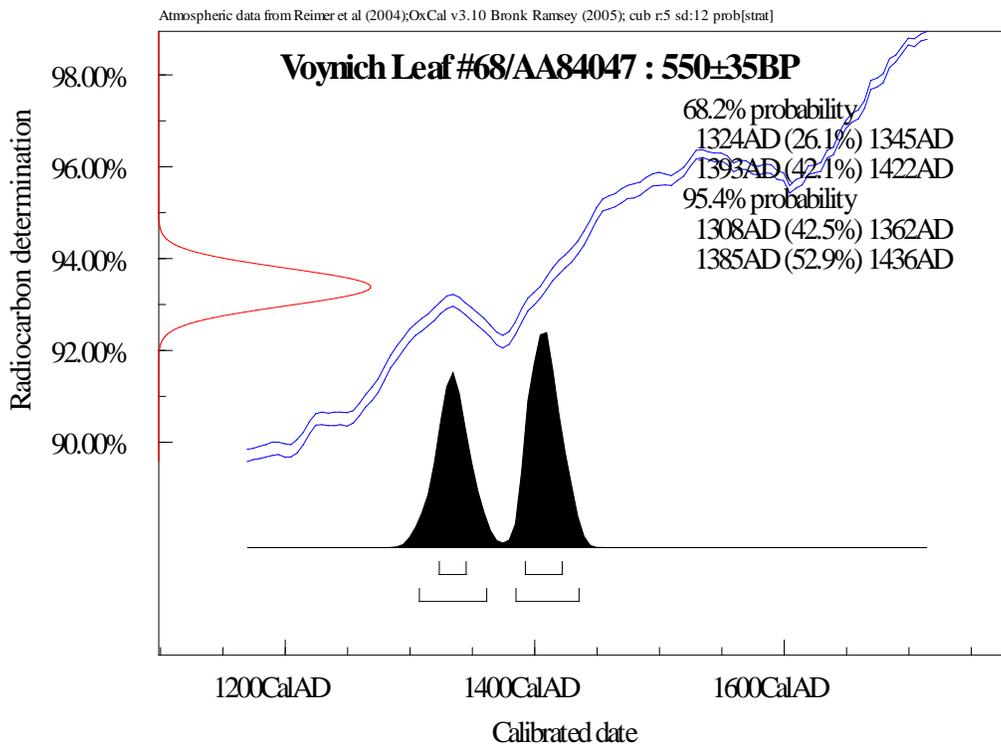

Figure 2: Leaf #26

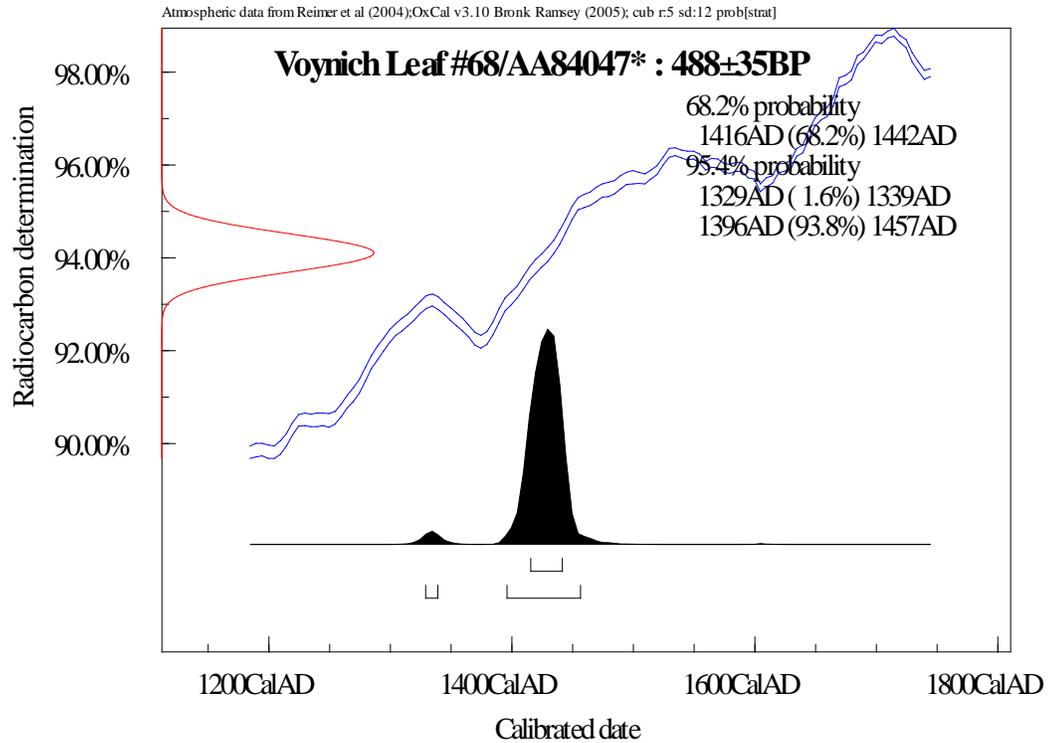Figure 3: Leaf #47

Figure 4: Leaf #68

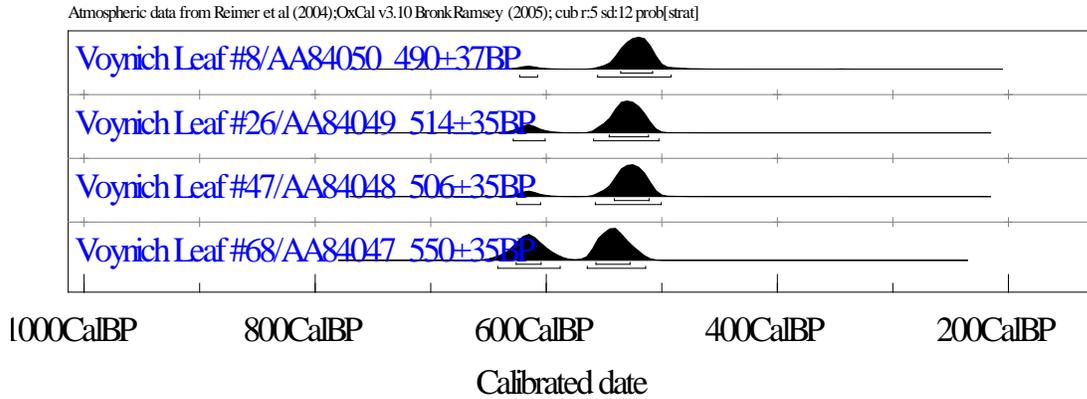Figure 5: Leaf #68, without solvent extraction

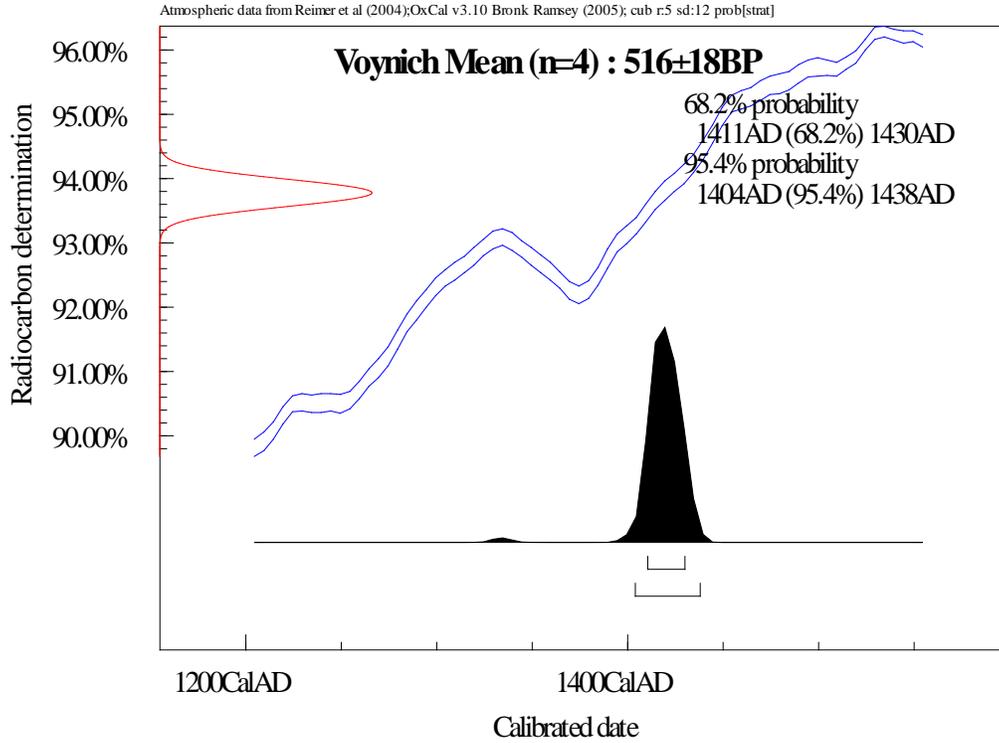Figure 6: Multiplot comparing age distributions of individual leaves

Figure 7: Weighted Mean Age (n=4) and Uncertainty

Table 1: Voynich Manuscript Samples

AA Number	Description	Sample Dry Mass (mg)	Sampling Location
AA84047	Leaf #68	10.82	LH edge, 0 cm to 2.5 cm from bottom
AA84048	Leaf #47	5.60	LH edge, 14 cm to 18.7 cm from top
AA84049	Leaf #26	5.88	RH edge, 3.5 cm to 6.7 cm, and 15.3 cm to 19.5 cm from top
AA84050	Leaf #8	7.84	LH edge, 12 cm to 17 cm from top

Table 2: Voynich Manuscript Measurements

AA Number	Description	Treated Sample Mass (mg)	Material	$\delta^{13}C$ (± 0.1‰)	Isotope Fractionation Corrected Fraction modern (FM)	Radiocarbon Age (yrs BP)
AA84047	Leaf #68	3.23	parchment	-22.4	0.9338 ± 0.0041	550 ± 35
AA84047	Leaf #68, no solvent extraction	2.18	parchment	-21.4	0.9410 ± 0.0041	488 ± 35
AA84048	Leaf #47	2.38	parchment	-23.0	0.9389 ± 0.0041	506 ± 35
AA84049	Leaf #26	2.05	parchment	-23.3	0.9380 ± 0.0041	514 ± 35
AA84050	Leaf #8	3.08	parchment	-22.6	0.9409 ± 0.0044	490 ± 37