SI Text

Horseshoe Lake Carbonates

The calcite measured in HSL is inferred to be predominantly endogenic, with minimal detrital input. Ideally calcite would be checked for euhedral shape, pitting, and/or overgrowths to determine whether it formed in the water column or was transported. However, the clay matrix and low percentage of calcite (3-8%) makes finding individual calcite crystals with optical microscopy and SEM difficult. The few crystals that could be confirmed as calcite were very small (fine silt size) and fairly euhedral. But the data were not unequivocal. Therefore, our assumption that the calcite is endogenic is based on several lines of evidence. None are individually compelling but taken as a whole, we believe they support the inference that we have a primary climatic record:

1. The isotopic record for the period of Cahokia's peak and decline mirrors that of Martin Lake, Indiana, a kettle lake system with less potential for detrital input and outside of our primary catchment (1). The correspondence and timing strongly suggest a coherent regional climate signal.
2. Modest covariance of the $\delta^{18}O$ and $\delta^{13}C$ values for 15HSL (Figs. S1 and S2) suggests either a single source of calcite or mixing between two source end-members. In the latter scenario, if one source is endogenic then the other would need to be a fairly uniform detrital component. The main source of terrigenous material into this section of the lake is Cahokia Creek, which drains the bluff to the east of the flood plain and has made a prograding delta into the arm of Horseshoe Lake from which 15HSL was taken. We do not take into consideration flooding events of the Mississippi and Missouri Rivers, for which we cannot constrain the source of the detrital calcite. However, these would not be common events as noted by Munoz et al.'s (2) reconstruction of flood events. The bluffs are composed of the Pennsylvanian Age Shelburn Formation underlain by the Carbondale Formation (Moscovian) (3). Both units are mainly shales and siltstones with lime mudstones and thin interbedded limestones. Although we can find no direct data on the isotopic value of these units, Popp et al. (4) compiled data from various sources that span the Pennsylvanian. Whole fossils from the Moscovian of Oklahoma had $\delta^{18}O$ values of -2 to 0 ‰ and $\delta^{13}C$ values were 0 to +2 ‰, respectively. Admittedly this is a small sample size and does not account for the general isotopic value of the muds, but the values do tightly overlap with limestones from Spain suggesting a more or less global value (4). Given that these values are significantly more enriched than those of HSL, we conclude that detrital limestones cannot be the sole source of material. They do not refute a mixture, however. In the case of a mixture, the higher $\delta^{18}O$ values in the 11th century CE would reflect more detrital input and the low values in the 12th century would reflect less detrital input of carbonates. However, the mineral percentages and carbonate percentages are relatively uniform across this entire interval at 85 ± 2 % and 4.9 ± 0.9 %, respectively, including data from flood event V.
3. There is no correlation between the amount of calcite and the isotopic value. Nor do we see increases in % calcite during flood events. Flood event V did not change the % carbonate value but did increase the mineral content by 4%. If floods and Cahokia creek were bringing in significant amounts of detrital carbonates, which we do not believe they are, then the isotopes should respond accordingly.
4. Finally, the chemistry of the lake is suitable for generating endogenic carbonates. A pH of ~9 has been observed in the modern system (5). Shell material and ostracodes are common in most core levels.

www.pnas.org/cgi/doi/10.1073/pnas.1809400116

Loss-on-Ignition Methodology. We prepared 36 15HSL samples for loss-on-ignition (LOI) analysis to correlate changes in the relative amounts of organic carbon, inorganic carbon ($CaCO_3$), and other minerals with those displayed by HORM12 LOI data (Fig. S3) (6). We freeze dried the samples, burned them in a furnace at 550°C for 4 hours to remove organic carbon, and then burned them once more at 1000°C for 2 hours to remove carbonate minerals. We weighed the samples between each treatment to determine the percent organic, carbonate, and mineral content of each sample (Table S2).

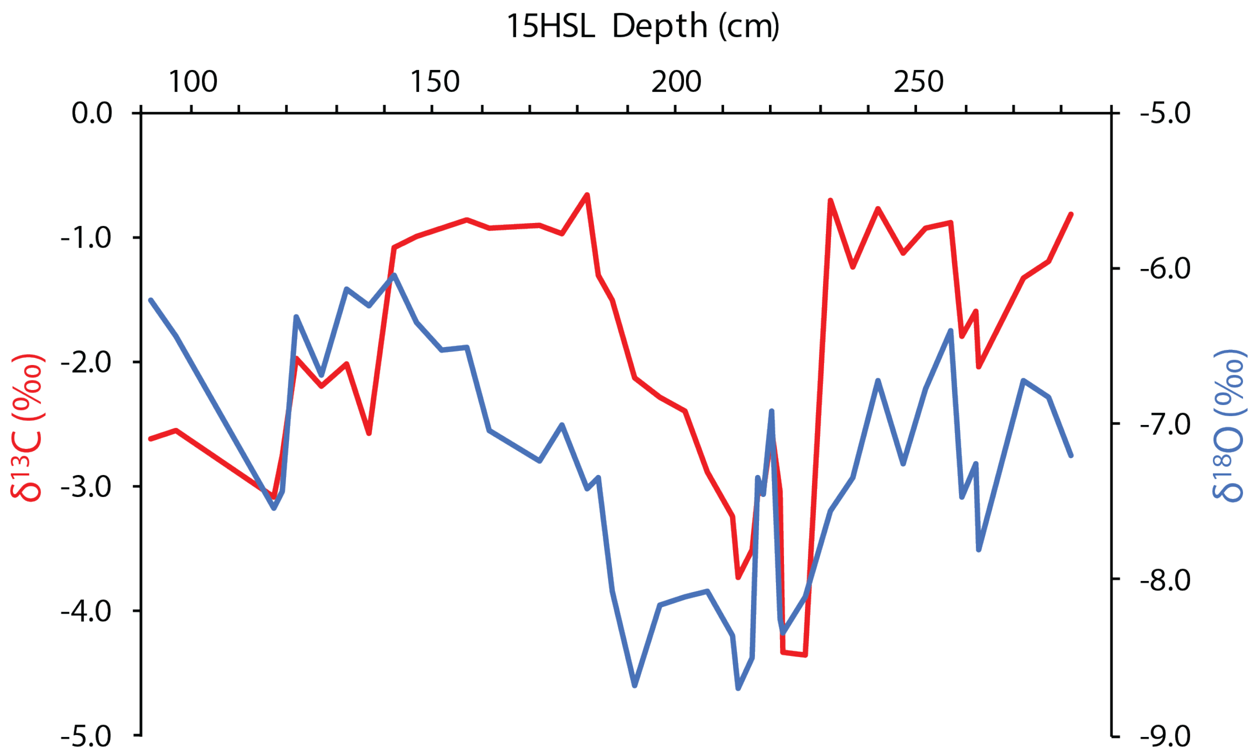

Fig. S1. 15HSL δ^{18}O and δ^{13}C values.

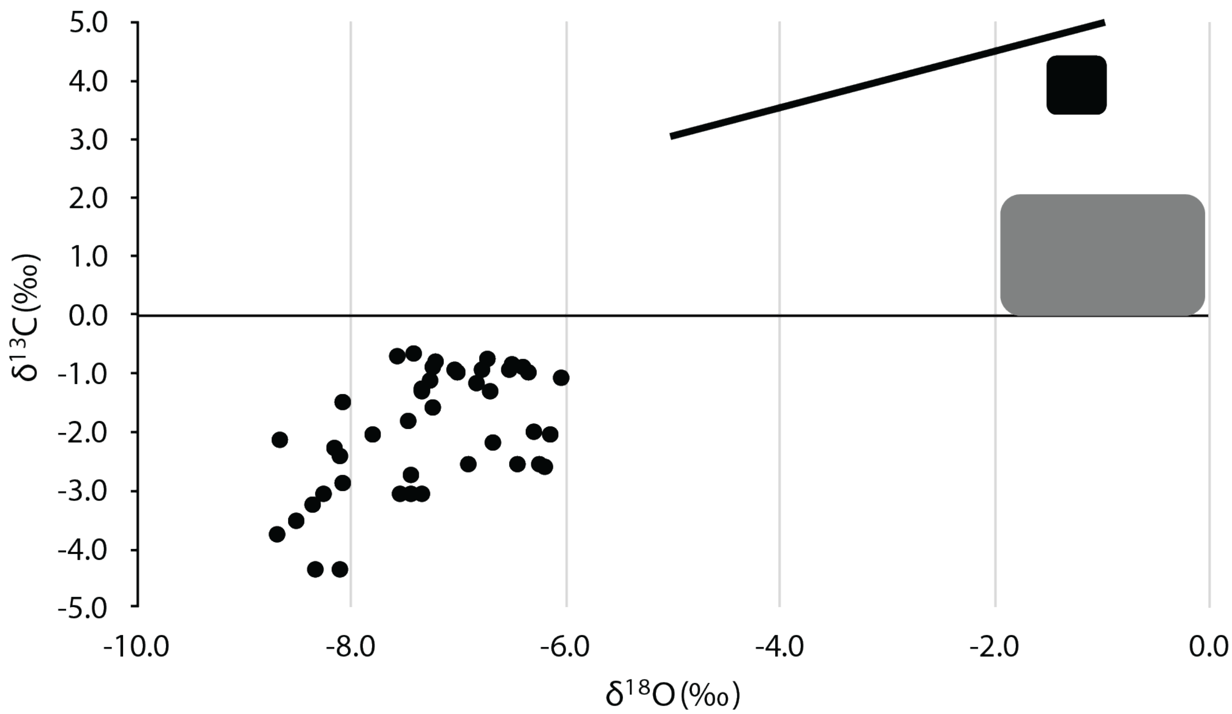

Fig. S2. 15HSL $\delta^{18}O$ and $\delta^{13}C$ values (black points) compared to isotopic values of fossils from Carboniferous limestones of Missouri/Illinois (diagonal black line) (7), Carboniferous micritic calcite from New Mexico, taken by others as the actual ocean value (black square) (8), and whole fossils from the Carbondale Formation (gray rectangle) (4).

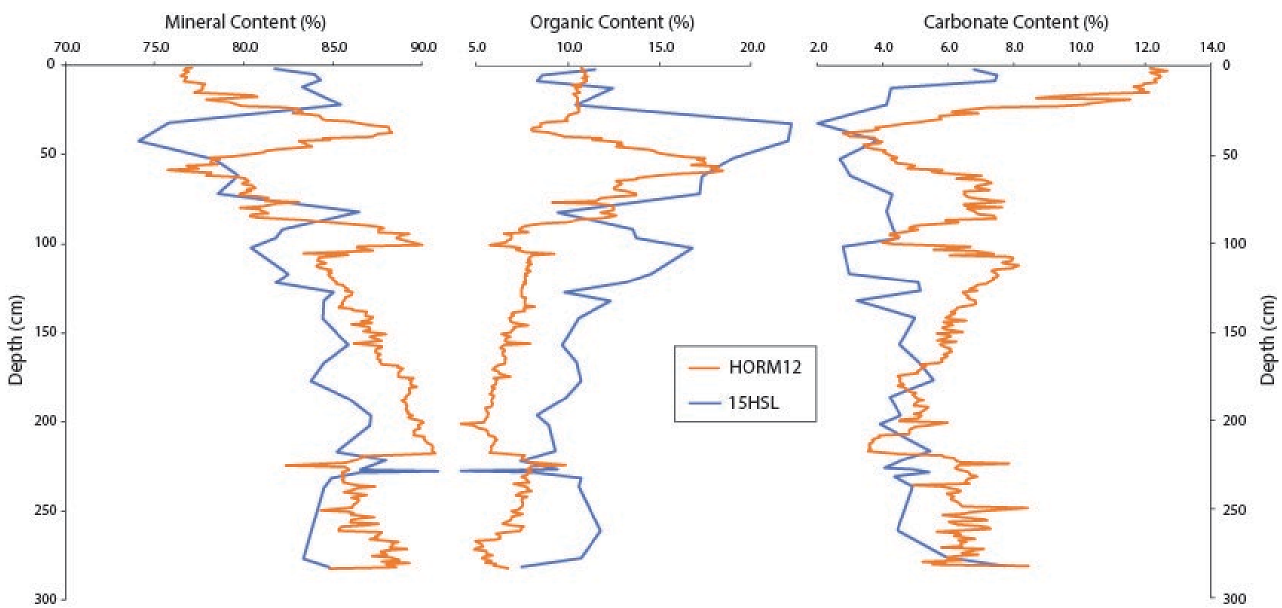

Fig.` S3. Correlation of LOI 15HSL (blue line) and HORM12 (orange line) (6) data.

Table S1. 15HSL $\delta^{18}O_c$ Data

Age (Calibrated Year CE; Munoz et al., 2014)	15HSL Core Depth (cm)	$\delta^{18}O_c$ (‰)

1861	2	-6.10
1526	92	-6.21
1520	97	-6.44
1467	117	-7.55
1461	119	-7.44
1452	122	-6.73
1436	127	-6.68
1421	132	-6.85
1405	137	-6.25
1389	142	-6.05
1374	147	-6.34
1358	152	-6.53
1343	157	-6.51
1327	162	-7.04
1296	172	-7.23
1281	177	-7.01
1265	182	-7.42
1259	184	-7.34
1249	187	-8.08
1234	192	-8.67
1218	197	-8.17
1202	202	-8.11
1187	207	-8.46
1171	212	-9.31
1168	213	-8.70
1159	216	-8.51
1156	217	-7.28
1156	218	-7.45
1155	220	-6.92
1155	222	-8.86
1154	222.5	-8.35
1153	227	-8.11
1134	232	-7.57
1115	237	-7.35
1095	242	-6.73
1076	247	-7.26
1057	252	-6.78
1038	257	-6.40
1030	259	-7.47
1019	262	-7.25
1015	263	-7.81

980	272	-6.72
961	277	-6.82
946	282	-7.21

Table S2. 15HSL LOI data.

Sample depth (cm)	Organic content (%)	Carbonate content (%)	Mineral content (%)
2	11.5	6.8	81.7
5	8.6	7.5	83.9
8	8.3	7.4	84.3
12	12.5	4.2	83.3
22	10.4	4.1	85.5
32	22.2	2.0	75.8
42	22.0	3.8	74.1
52	19.0	2.7	78.3
62	17.3	3.0	79.7
72	17.2	4.3	78.5
82	9.4	4.1	86.5
92	13.5	4.3	82.2
97	13.7	4.5	81.8
102	16.8	2.8	80.4
117	14.5	3.0	82.5
121.5	13.1	5.1	81.8
127	9.8	5.1	85.0
132	12.3	3.2	84.5
142	10.6	5.0	84.4
157	9.7	4.5	85.8
167	10.5	5.1	84.5
177	10.7	5.5	83.8
187	9.8	4.2	85.9
197	8.3	4.6	87.1
202	9.0	3.9	87.1
217	9.3	5.5	85.2
222	7.4	4.6	88.0
227	9.4	4.1	86.5
227.8	4.2	4.9	90.9
229	8.1	5.4	86.5
232	10.7	4.4	84.9
237	10.6	4.9	84.5
262	11.8	4.4	83.8

277	10.7	5.9	83.3
282	7.5	7.8	84.8

Table S3. ^{14}C dates from Horseshoe Lake sediment core HORM12 (6).

Lab Number	Sample Description	Depth (cm)	^{14}C age*
UGAMS-13417	wood	111.5	400 ± 25
UGAMS-13418	wood	197.5	980 ± 40
UGAMS-14454	wood	225	800 ± 20
UGAMS-13419	wood	254.5	1220 ± 25
UGAMS-15039	charcoal	256.5	990 ± 25
UGAMS-15040	charcoal	285.5	990 ± 25
UGAMS-15041	charcoal	298.5	1370 ± 25
DAMS-005563	charcoal	330	1316 ± 24
UGAMS-13420	wood	347.5	3560 ± 30
UGAMS-14455	wood	377.5	1620 ± 25
UGAMS-14456	wood	389.5	1650 ± 25

*Uncalibrated ages in radiocarbon years before 1950 (years BP), using the ^{14}C half–life of 5,568 years. The error is one standard deviation and each date has been corrected for isotope fractionation.

Table S4. HORM12 mass accumulation rates (9).

Depth (cm)	clam_accrate (cm/yr)	wt_mineral (g/cm)	influx_clam (g/cm^2/yr)
0.5	5.92	0.3011	0.0509
1.5	5.92	0.2925	0.0494
2.5	5.92	0.2951	0.0499
3.5	5.92	0.2898	0.0490
4.5	5.92	0.2858	0.0483
5.5	5.91	0.2937	0.0497
6.5	5.90	0.2870	0.0486
7.5	5.90	0.2848	0.0483
8.5	5.89	0.3032	0.0515
9.5	5.88	0.3110	0.0529
10.5	5.87	0.3255	0.0555
11.5	5.86	0.3240	0.0553
12.5	5.85	0.3360	0.0574
13.5	5.84	0.3156	0.0540
14.5	5.82	0.3159	0.0543
15.5	5.81	0.3446	0.0593
16.5	5.79	0.3826	0.0661
17.5	5.77	0.3903	0.0676

18.5	5.76	0.3252	0.0565
19.5	5.74	0.3187	0.0555
20.5	5.72	0.3474	0.0607
21.5	5.70	0.3377	0.0592
22.5	5.68	0.3603	0.0634
23.5	5.65	0.3733	0.0661
24.5	5.63	0.3707	0.0658
25.5	5.61	0.3882	0.0692
26.5	5.58	0.3913	0.0701
27.5	5.55	0.4012	0.0723
28.5	5.53	0.4129	0.0747
29.5	5.50	0.4310	0.0784
30.5	5.47	0.4266	0.0780
31.5	5.44	0.4494	0.0826
32.5	5.41	0.4581	0.0847
33.5	5.37	0.4543	0.0846
34.5	5.34	0.4803	0.0900
35.5	5.31	0.4988	0.0939
36.5	5.27	0.4974	0.0944
37.5	5.24	0.5019	0.0958
38.5	5.20	0.4828	0.0928
39.5	5.17	0.4638	0.0897
40.5	5.14	0.3673	0.0715
41.5	5.10	0.3850	0.0755
42.5	5.07	0.3288	0.0649
43.5	5.04	0.3458	0.0686
44.5	5.00	0.3521	0.0704
45.5	4.97	0.3549	0.0714
46.5	4.94	0.2943	0.0596
47.5	4.90	0.2946	0.0601
48.5	4.87	0.2925	0.0601
49.5	4.84	0.2915	0.0602
50.5	4.80	0.2691	0.0561
51.5	4.77	0.2477	0.0519
52.5	4.74	0.2467	0.0520
53.5	4.71	0.2437	0.0517
54.5	4.68	0.2360	0.0504
55.5	4.64	0.2430	0.0524
56.5	4.61	0.2301	0.0499
57.5	4.58	0.2296	0.0501
58.5	4.55	0.2328	0.0512
59.5	4.52	0.2398	0.0531
60.5	4.49	0.2605	0.0580
61.5	4.45	0.2677	0.0602
62.5	4.42	0.2865	0.0648

63.5	4.39	0.2962	0.0675
64.5	4.36	0.3084	0.0707
65.5	4.33	0.3156	0.0729
66.5	4.30	0.3164	0.0736
67.5	4.27	0.3234	0.0757
68.5	4.24	0.3149	0.0743
69.5	4.21	0.3110	0.0739
70.5	4.18	0.3131	0.0749
71.5	4.15	0.3168	0.0763
72.5	4.12	0.3022	0.0733
73.5	4.09	0.3231	0.0790
74.5	4.06	0.3687	0.0908
75.5	4.03	0.3436	0.0853
76.5	4.00	0.3736	0.0934
77.5	3.97	0.3577	0.0901
78.5	3.94	0.3571	0.0906
79.5	3.91	0.3415	0.0874
80.5	3.88	0.3436	0.0886
81.5	3.85	0.3562	0.0925
82.5	3.82	0.3623	0.0948
83.5	3.80	0.3567	0.0939
84.5	3.77	0.3347	0.0888
85.5	3.74	0.3432	0.0918
86.5	3.71	0.3877	0.1045
87.5	3.68	0.4070	0.1106
88.5	3.65	0.4532	0.1242
89.5	3.63	0.4727	0.1302
90.5	3.60	0.4967	0.1380
91.5	3.57	0.4919	0.1378
92.5	3.54	0.4924	0.1391
93.5	3.51	0.4829	0.1376
94.5	3.49	0.5862	0.1680
95.5	3.46	0.5487	0.1586
96.5	3.43	0.5281	0.1540
97.5	3.41	0.5435	0.1594
98.5	3.38	0.5734	0.1696
99.5	3.35	0.6019	0.1797
100.5	3.33	0.5865	0.1761
101.5	3.30	0.4633	0.1404
102.5	3.27	0.4705	0.1439
103.5	3.25	0.4961	0.1526
104.5	3.22	0.4799	0.1490
105.5	3.19	0.3932	0.1233
106.5	3.17	0.4695	0.1481
107.5	3.14	0.4565	0.1454

108.5	3.12	0.4531	0.1452
109.5	3.09	0.4617	0.1494
110.5	3.07	0.4765	0.1552
111.5	3.04	0.4715	0.1551
112.5	3.02	0.4516	0.1495
113.5	2.99	0.4524	0.1513
114.5	2.97	0.4671	0.1573
115.5	2.95	0.4719	0.1600
116.5	2.93	0.4804	0.1640
117.5	2.91	0.4444	0.1527
118.5	2.90	0.4420	0.1524
119.5	2.88	0.4587	0.1593
120.5	2.87	0.4538	0.1581
121.5	2.85	0.4664	0.1636
122.5	2.84	0.5074	0.1787
123.5	2.83	0.4790	0.1693
124.5	2.82	0.4789	0.1698
125.5	2.82	0.4750	0.1684
126.5	2.81	0.4717	0.1679
127.5	2.81	0.4690	0.1669
128.5	2.80	0.4747	0.1695
129.5	2.80	0.4755	0.1698
130.5	2.80	0.4680	0.1672
131.5	2.80	0.4668	0.1667
132.5	2.80	0.4537	0.1620
133.5	2.81	0.4620	0.1644
134.5	2.81	0.4780	0.1701
135.5	2.82	0.4490	0.1592
136.5	2.82	0.4681	0.1660
137.5	2.83	0.4819	0.1703
138.5	2.84	0.4739	0.1669
139.5	2.85	0.4776	0.1676
140.5	2.87	0.5008	0.1745
141.5	2.88	0.4922	0.1709
142.5	2.90	0.4703	0.1622
143.5	2.91	0.4890	0.1680
144.5	2.93	0.5078	0.1733
145.5	2.95	0.4598	0.1559
146.5	2.97	0.4863	0.1637
147.5	2.99	0.4893	0.1636
148.5	3.02	0.4799	0.1589
149.5	3.04	0.4935	0.1623
150.5	3.07	0.5128	0.1670
151.5	3.10	0.5214	0.1682
152.5	3.12	0.4827	0.1547

153.5	3.15	0.5066	0.1608
154.5	3.19	0.5048	0.1582
155.5	3.22	0.4970	0.1543
156.5	3.25	0.4639	0.1427
157.5	3.29	0.5168	0.1571
158.5	3.32	0.5479	0.1650
159.5	3.36	0.5434	0.1617
160.5	3.40	0.5217	0.1535
161.5	3.44	0.5269	0.1532
162.5	3.48	0.5303	0.1524
163.5	3.53	0.5319	0.1507
164.5	3.57	0.5133	0.1438
165.5	3.62	0.5280	0.1459
166.5	3.67	0.5266	0.1435
167.5	3.72	0.5372	0.1444
168.5	3.77	0.5573	0.1478
169.5	3.82	0.5845	0.1530
170.5	3.87	0.6012	0.1553
171.5	3.92	0.5697	0.1453
172.5	3.98	0.5600	0.1407
173.5	4.04	0.5591	0.1384
174.5	4.09	0.5500	0.1345
175.5	4.15	0.5601	0.1350
176.5	4.21	0.5390	0.1280
177.5	4.28	0.5533	0.1293
178.5	4.34	0.5562	0.1282
179.5	4.40	0.5854	0.1330
180.5	4.47	0.5883	0.1316
181.5	4.54	0.5787	0.1275
182.5	4.61	0.5761	0.1250
183.5	4.68	0.5898	0.1260
184.5	4.75	0.5731	0.1207
185.5	4.82	0.5631	0.1168
186.5	4.89	0.5773	0.1181
187.5	4.97	0.5760	0.1159
188.5	5.05	0.5760	0.1141
190.5	5.20	0.5874	0.1130
191.5	5.28	0.6083	0.1152
192.5	5.37	0.6045	0.1126
193.5	5.45	0.6092	0.1118
194.5	5.54	0.6223	0.1123
195.5	5.62	0.6182	0.1100
196.5	5.70	0.6621	0.1162
197.5	5.78	0.6420	0.1111
198.5	5.85	0.6176	0.1056

199.5	5.91	0.6423	0.1087
200.5	5.98	0.6284	0.1051
201.5	6.03	0.6405	0.1062
202.5	6.08	0.6262	0.1030
203.5	6.13	0.6346	0.1035
204.5	6.17	0.6352	0.1029
205.5	6.20	0.6451	0.1040
206.5	6.24	0.6679	0.1070
207.5	6.26	0.6765	0.1081
208.5	6.28	0.6706	0.1068
209.5	6.30	0.6538	0.1038
210.5	6.31	0.6492	0.1029
211.5	6.31	0.6368	0.1009
212.5	6.32	0.6208	0.0982
213.5	6.31	0.6110	0.0968
214.5	6.30	0.6234	0.0990
215.5	6.29	0.6332	0.1007
216.5	6.27	0.6339	0.1011
217.5	6.24	0.6627	0.1062
218.5	6.21	0.5715	0.0920
219.5	6.18	0.4936	0.0799
220.5	6.14	0.5102	0.0831
221.5	6.10	0.4814	0.0789
222.5	6.05	0.4709	0.0778
223.5	5.99	0.4664	0.0779
224.5	5.93	0.3695	0.0623
225.5	5.88	0.4610	0.0784
226.5	5.83	0.4683	0.0803
227.5	5.78	0.4703	0.0814
228.5	5.74	0.4639	0.0808
229.5	5.71	0.4712	0.0825
230.5	5.67	0.4793	0.0845
231.5	5.65	0.4689	0.0830
232.5	5.62	0.4835	0.0860
233.5	5.60	0.4732	0.0845
234.5	5.59	0.4662	0.0834
235.5	5.58	0.5148	0.0923
236.5	5.57	0.5049	0.0907
237.5	5.56	0.4701	0.0846
238.5	5.56	0.4589	0.0825
239.5	5.57	0.4472	0.0803
240.5	5.58	0.5051	0.0905
241.5	5.59	0.4999	0.0894
242.5	5.61	0.4685	0.0835
243.5	5.63	0.4747	0.0843

244.5	5.65	0.4754	0.0841
245.5	5.68	0.4733	0.0833
246.5	5.71	0.4702	0.0824
247.5	5.75	0.4775	0.0830
248.5	5.79	0.4703	0.0812
249.5	5.83	0.4726	0.0811
250.5	5.88	0.4867	0.0828
251.5	5.94	0.4909	0.0826
252.5	5.99	0.4694	0.0784
253.5	6.05	0.5009	0.0828
254.5	6.12	0.4918	0.0804
255.5	6.19	0.5015	0.0810
256.5	6.25	0.4846	0.0775
257.5	6.29	0.5355	0.0851
258.5	6.32	0.4861	0.0769
259.5	6.32	0.4118	0.0652
260.5	6.32	0.4501	0.0712
261.5	6.29	0.4271	0.0679
262.5	6.24	0.5243	0.0840
263.5	6.18	0.5414	0.0876
264.5	6.10	0.5505	0.0902
265.5	6.00	0.5782	0.0964
266.5	5.88	0.5963	0.1014
267.5	5.74	0.7388	0.1287
268.5	5.59	0.6902	0.1235
269.5	5.43	0.6968	0.1283
270.5	5.28	0.6999	0.1326
271.5	5.13	0.7398	0.1442
272.5	4.99	0.6718	0.1346
273.5	4.86	0.6864	0.1412
274.5	4.73	0.6691	0.1415
275.5	4.61	0.6082	0.1319
276.5	4.49	0.6955	0.1549
277.5	4.38	0.7258	0.1657
278.5	4.28	0.6297	0.1471
279.5	4.18	0.7159	0.1713
280.5	4.08	0.6184	0.1516
281.5	4.00	0.7186	0.1797
282.5	3.92	0.6251	0.1595
283.5	3.84	0.7255	0.1889
284.5	3.78	0.8671	0.2294
285.5	3.71	0.6914	0.1864
286.5	3.66	0.6690	0.1828
287.5	3.61	0.6608	0.1831
288.5	3.56	0.6271	0.1762

289.5	3.53	0.6334	0.1794
290.5	3.49	0.6445	0.1847
291.5	3.47	0.6283	0.1811
292.5	3.45	0.6385	0.1851
293.5	3.44	0.6360	0.1849
294.5	3.43	0.6322	0.1843
295.5	3.43	0.6523	0.1902
296.5	3.43	0.6611	0.1927
297.5	3.44	0.6543	0.1902
298.5	3.46	0.6665	0.1926
299.5	3.48	0.6402	0.1840
300.5	3.51	0.6508	0.1854

1. Bird BW, Wilson JJ, Gilhooly Iii WP, Steinman BA, Stamps L (2017) Midcontinental Native American population dynamics and late Holocene hydroclimate extremes. *Scientific Reports* 7:41628.
2. Munoz SE, et al. (2015) Cahokia's emergence and decline coincided with shifts of flood frequency on the Mississippi River. *Proceedings of the National Academy of Sciences* 112(20):6319–6324.
3. Willman HB, et al. (1975) Handbook of Illinois stratigraphy. Available at: https://www.ideals.illinois.edu/handle/2142/35115.
4. Popp BN, Anderson TF, Sandberg PA (1986) Brachiopods as indicators of original isotopic compositions in some Paleozoic limestones. *Geological Society of America Bulletin* 97(10):1262.
5. Hill TE, Evans RL, Bell JS (1981) *Water quality assessment of Horseshoe Lake.* (Illinois Department of Conservation, Peoria, Illinois).
6. Munoz SE, Schroeder S, Fike DA, Williams JW (2014) A record of sustained prehistoric and historic land use from the Cahokia region, Illinois, USA. *Geology* 42(6):499–502.
7. Banner JL, Kaufman J (1994) The isotopic record of ocean chemistry and diagenesis preserved in non-luminescent brachiopods from Mississippian carbonate rocks, Illinois and Missouri. *GSA Bulletin* 106(8):1074–1082.
8. Schneidermann N, Harris PM eds. (1985) *Carbonate Cements* (SEPM (Society for Sedimentary Geology)) doi:10.2110/pec.85.36.
9. Munoz SE (2015) Forests, Fields, and Floods: A Historical Ecology of the Cahokia Region, Illinois, USA. Ph.D. (The University of Wisconsin - Madison, United States -- Wisconsin).